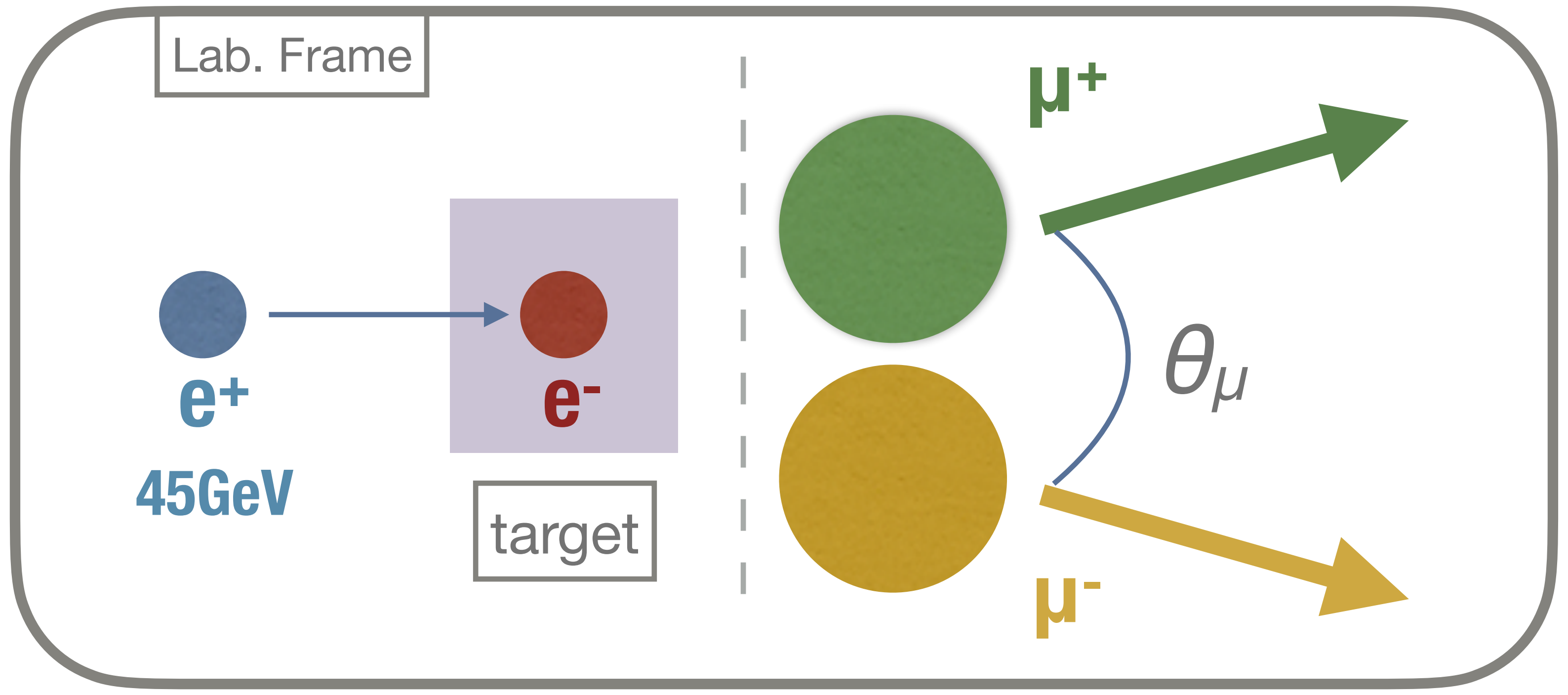
TARGET SYSTEM FOR COLLIMATED MUON BEAM PRODUCTION

M. Bauce, G. Cesarini, R. Li voti, G. Cavoto, F. Collamati, F. Casaburo, F. Anulli

APS April Meeting 2021, April 17-20 - Muon Collider Symposium

LEMMA NOVEL APPROACH

- **positron-driven** muon production:
  - asymmetric $e^+e^- \rightarrow \mu^+\mu^-$
  - above $\sqrt{s}$ = 0.212 GeV (i.e. 45 GeV e^+ beam on target)
  - low-emittance muon beam produced



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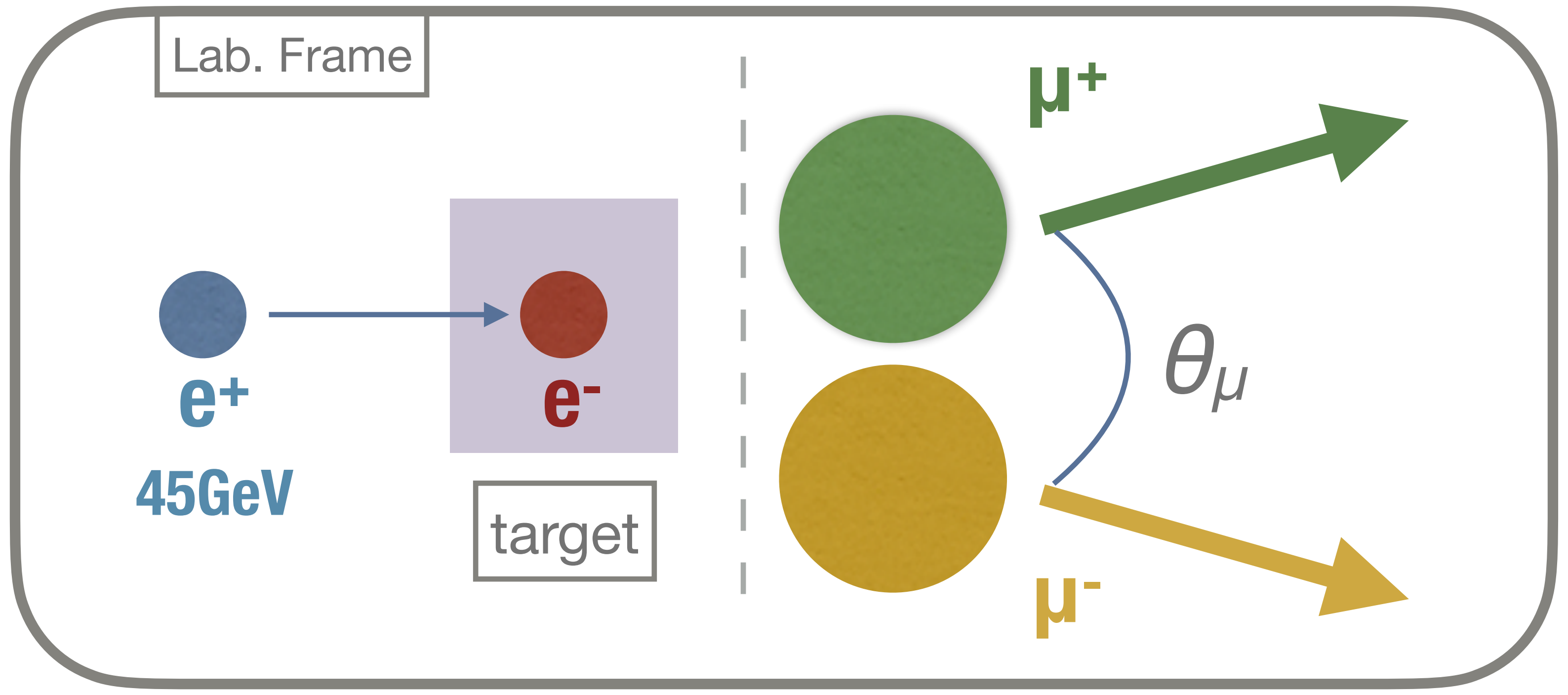

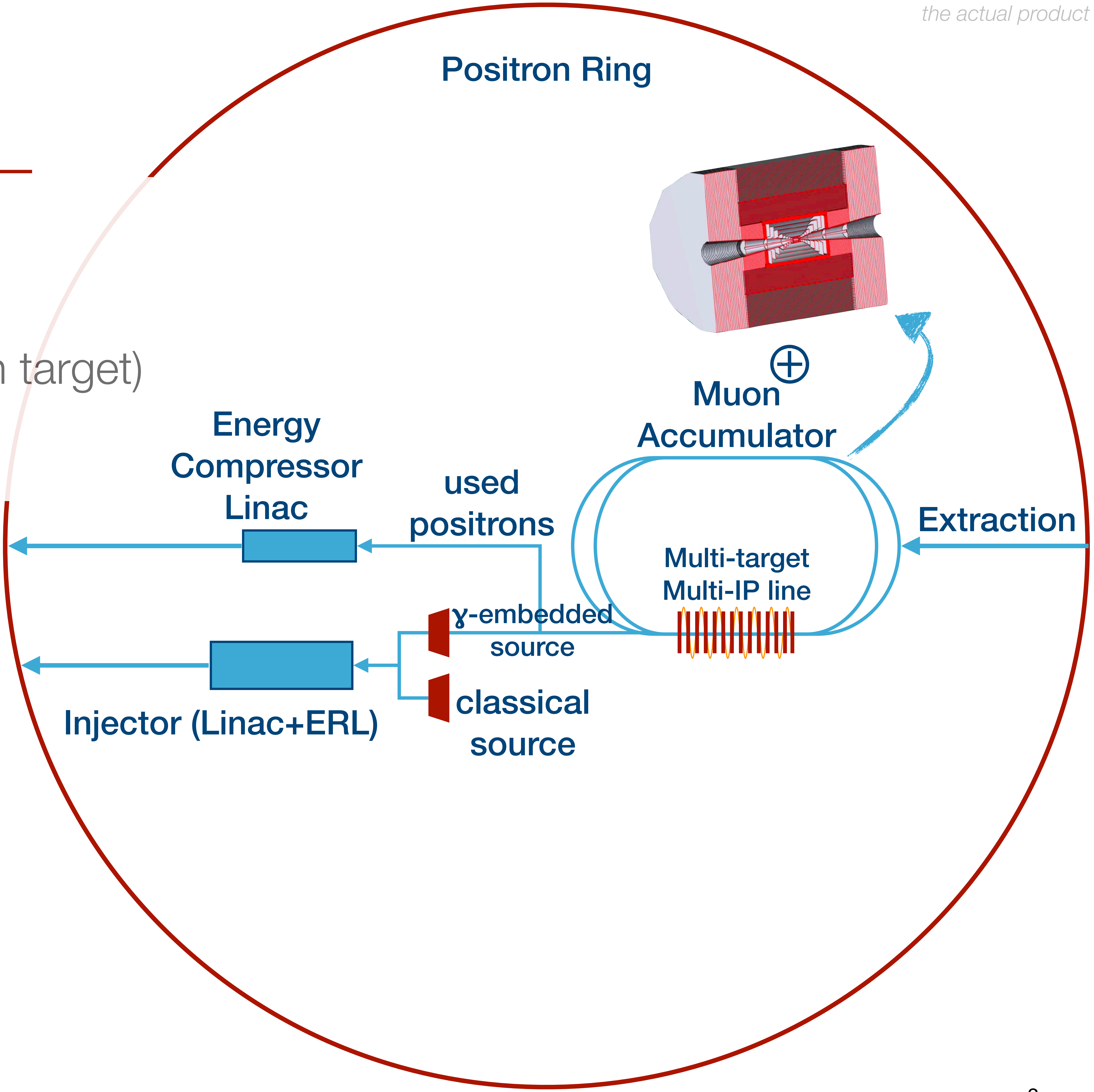

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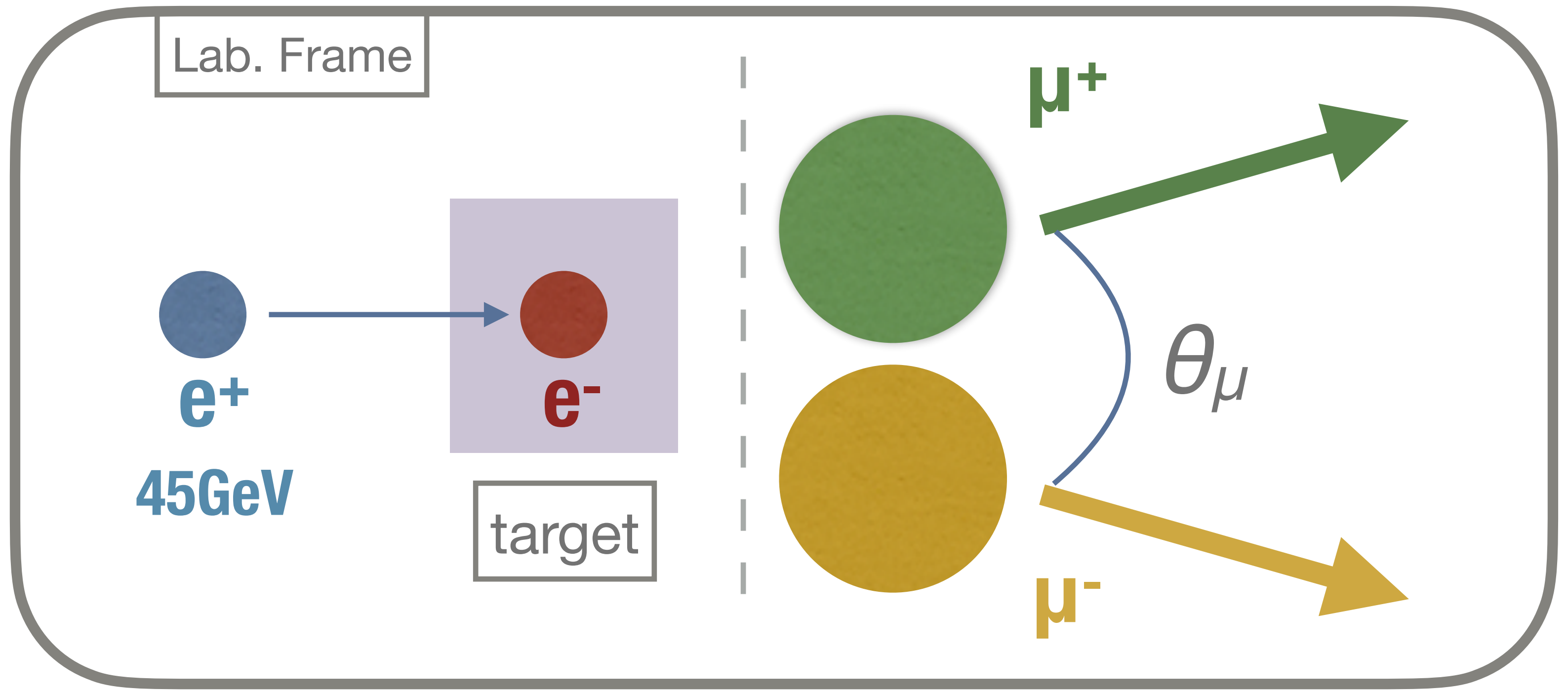
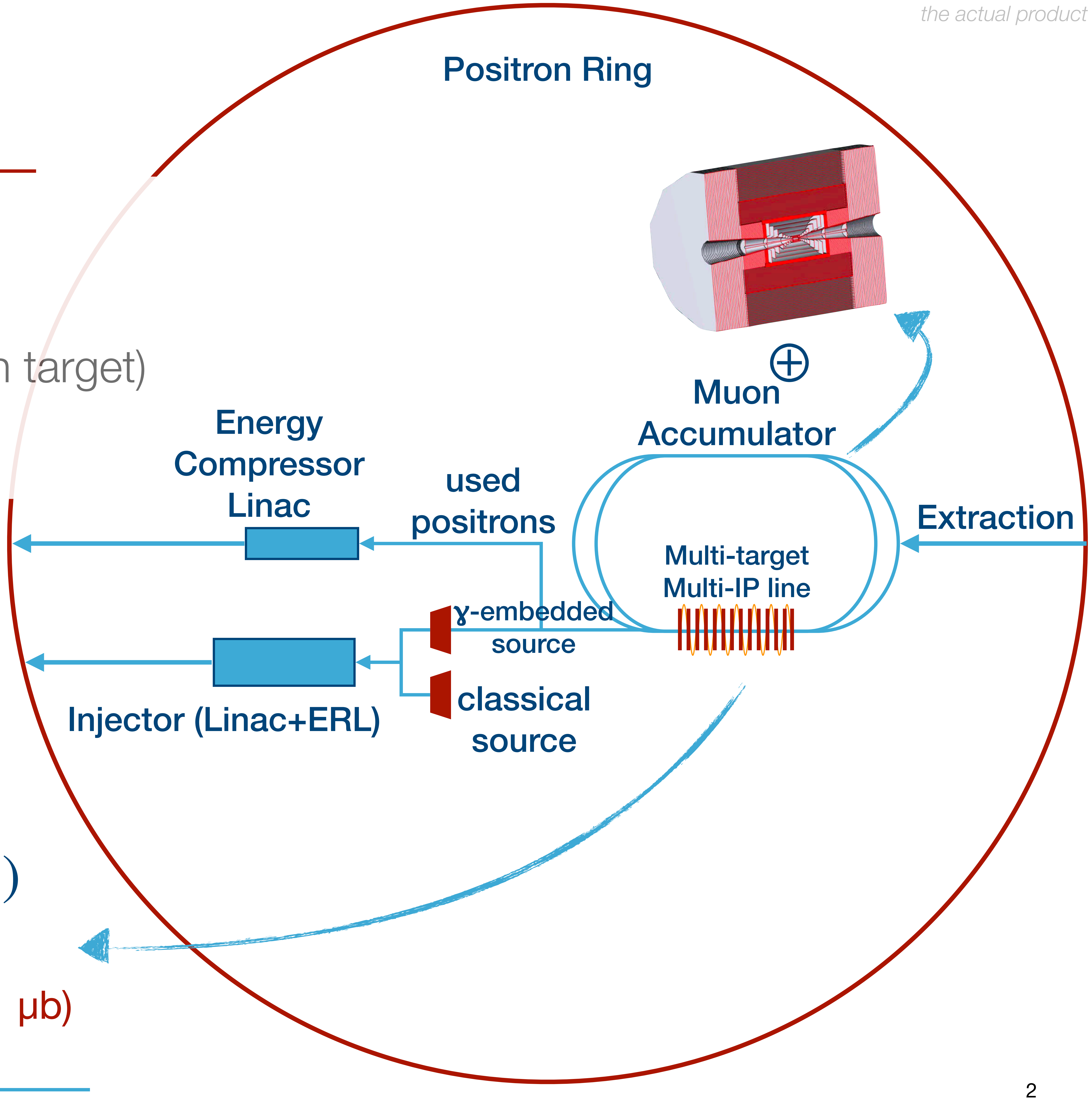


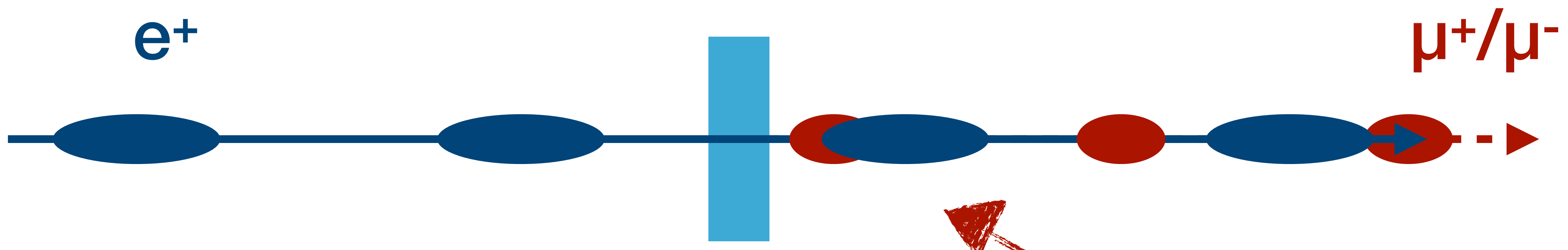
$$N_{\mu^+\mu^-} = \underbrace{N_{e+} \cdot \rho_{e-} \cdot L}_{} \cdot \sigma(e^+e^- \rightarrow \mu^+\mu^-)$$

Maximize the rest

Small cross section: O(1 μb)



MUON PRODUCTION ON TARGETS



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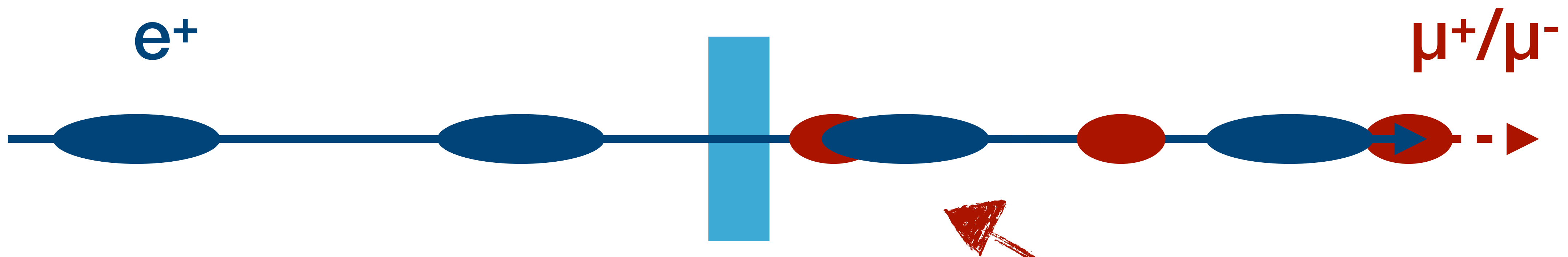

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Intermediate-Z materials: Be, C, Li

- low-emittance and small e^+ loss
- *decent* $\mu^+\mu^-$ production efficiency (**10^{-6}** $\mu^+\mu^-/e^+e^-$)

O(100 kW) power load

(with high Peak Energy Density Deposition)

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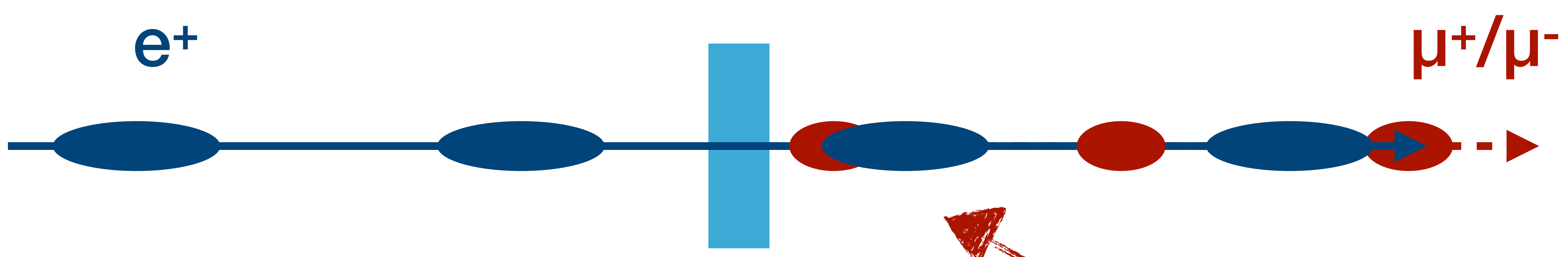

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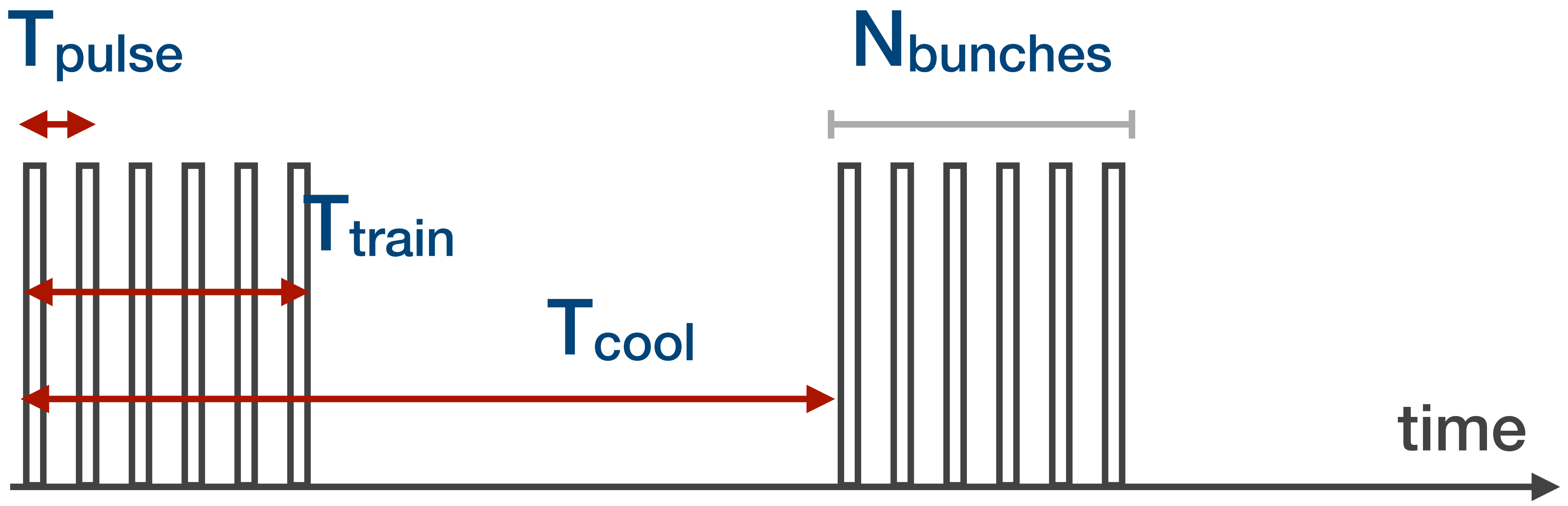
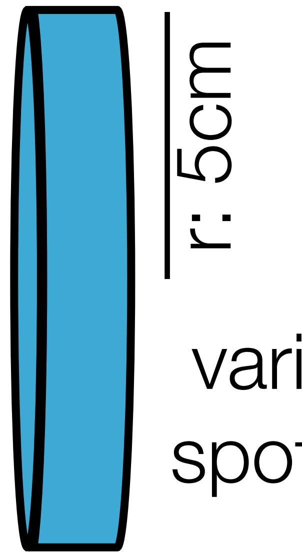
Simulated Benchmark Scenario
Bunch/Trains beam patterns

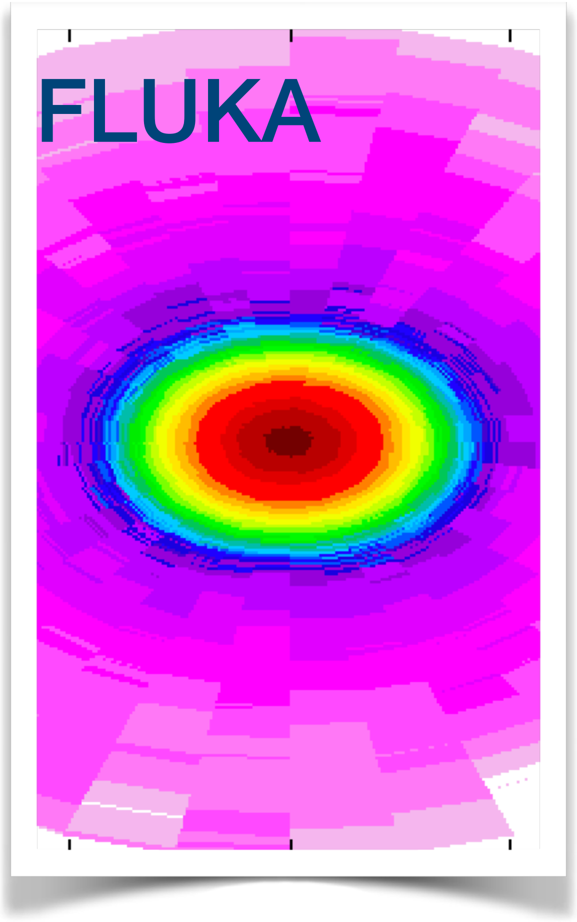
- N_{e+} : $3\text{x}10^{11}$ e^+/bunch
- bunch duration: 10 ps
- $N_{bunches}$: 100
- T_{pulse}: 400 ns (between bunches)
- $T_{train} = T_{pulse} \cdot N_{bunches}$: 40 μs
- T_{rep} = 0.1 s

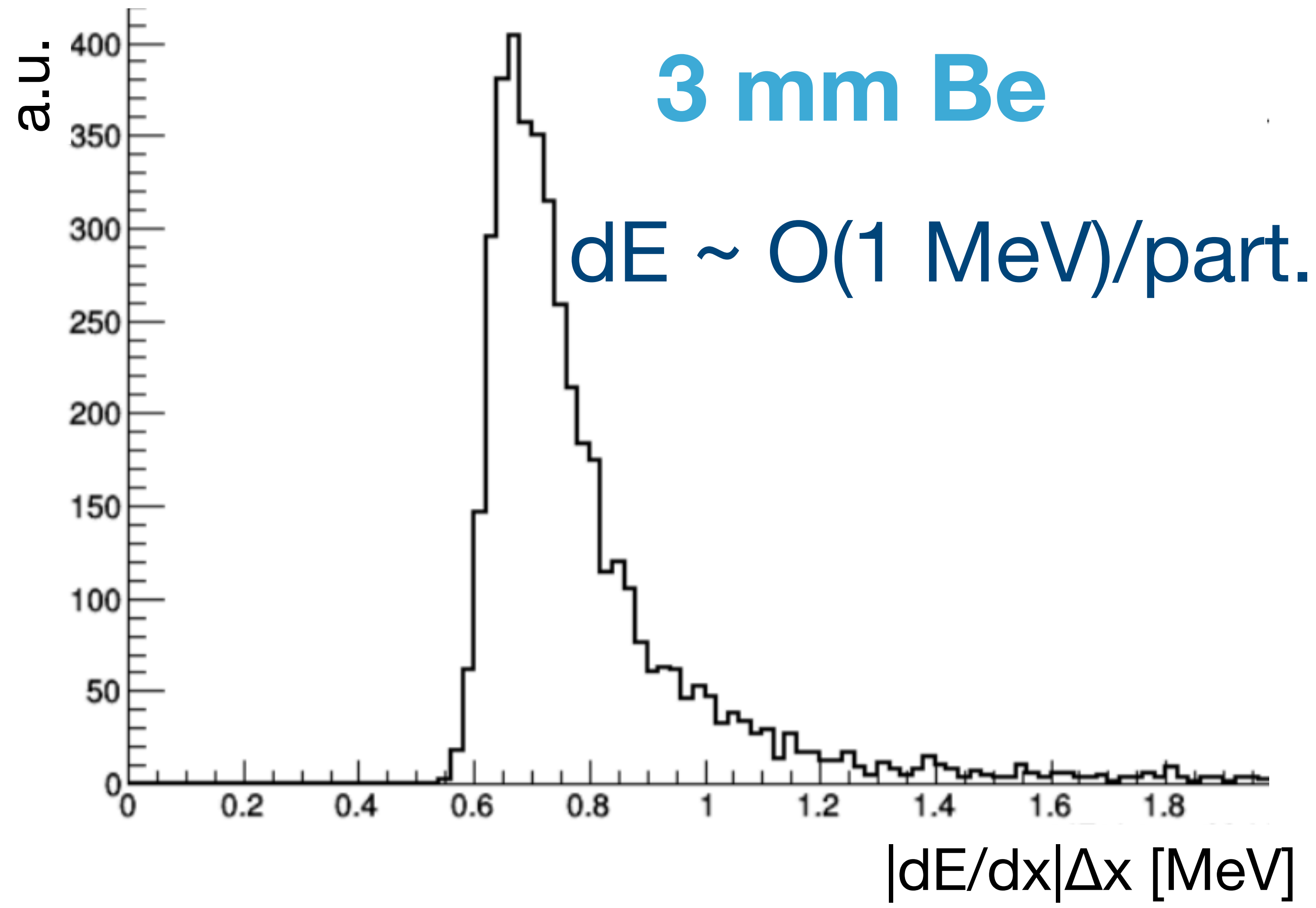


- Target: 3 mm thick Be, 1 mm thick C

ENERGY DEPOSIT SIMULATION







- FLUKA simulation of deposited energy from a single positron bunch
- Converted into Heat density for different target materials and thicknesses

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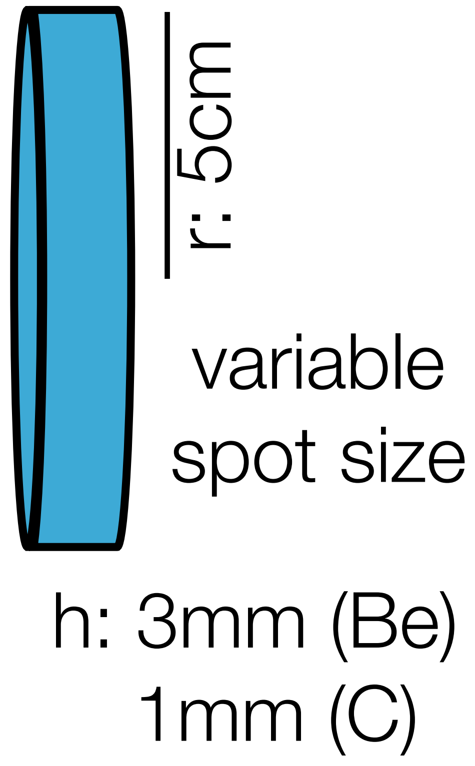

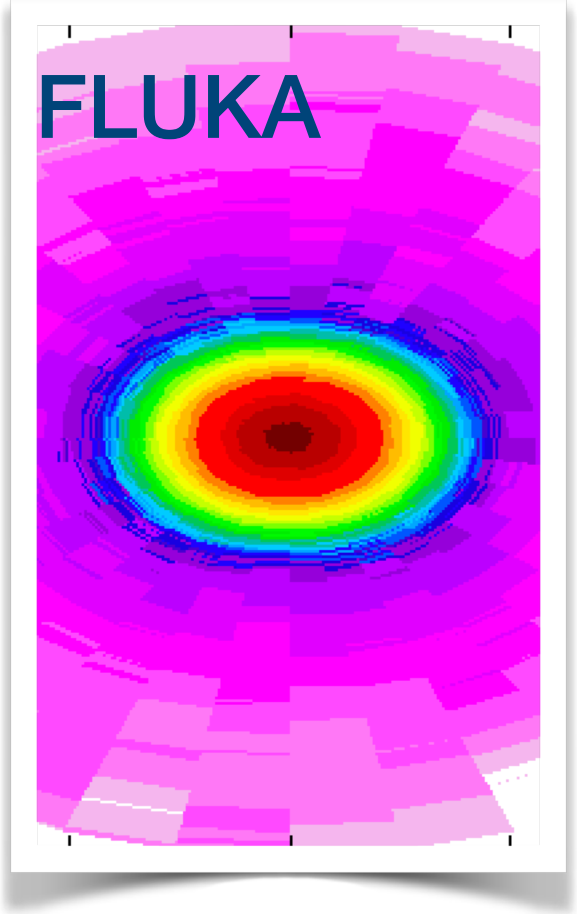

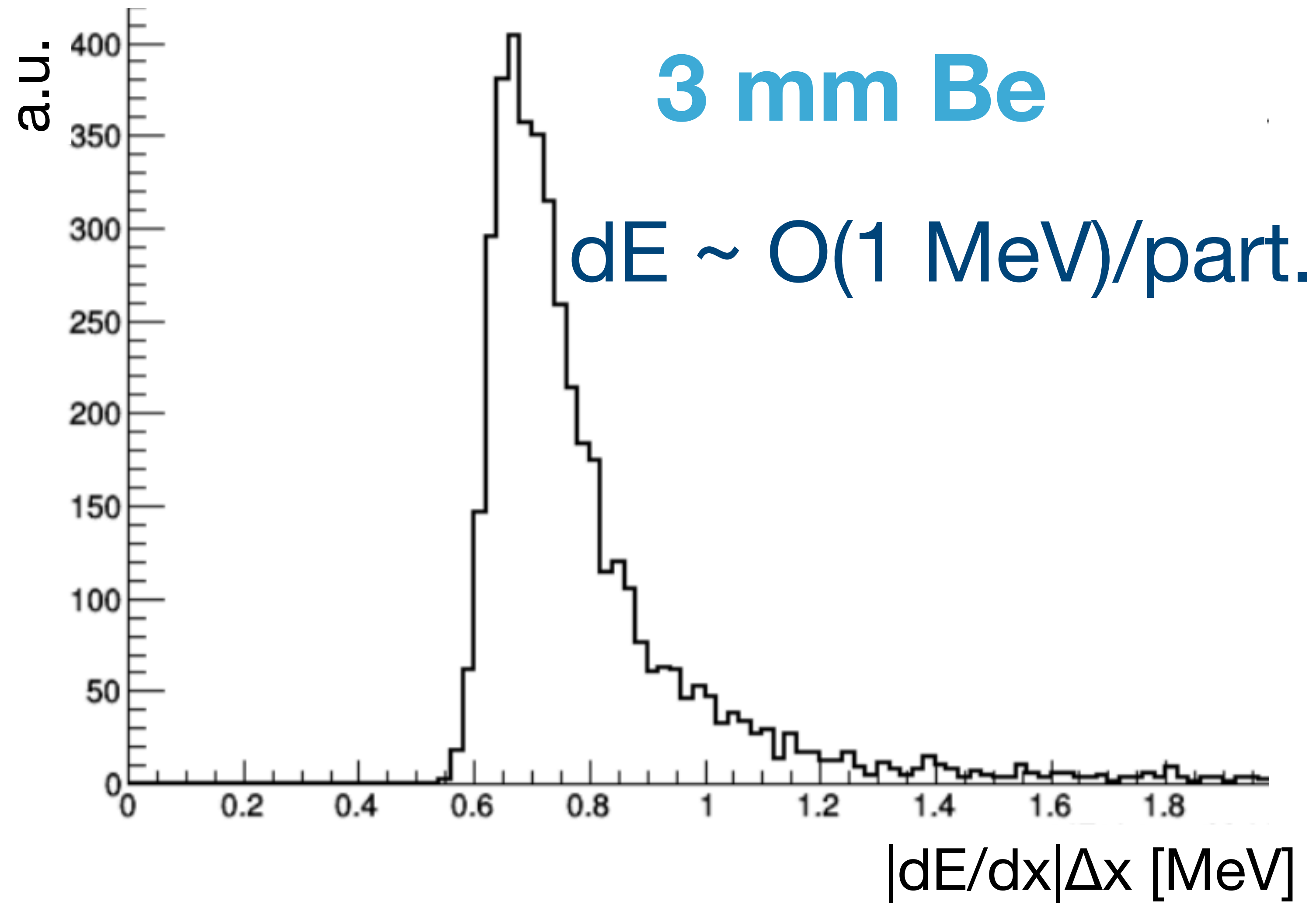

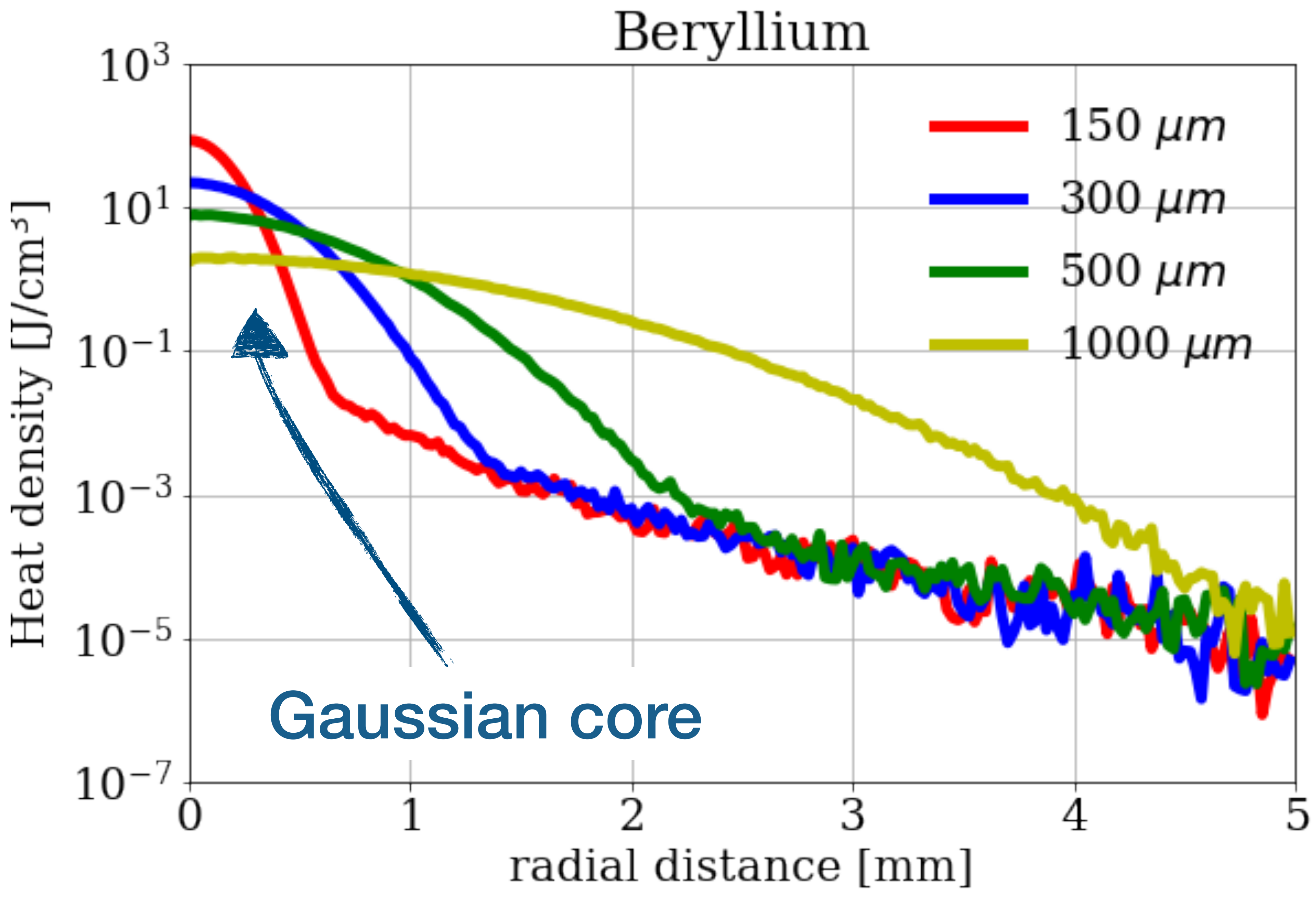

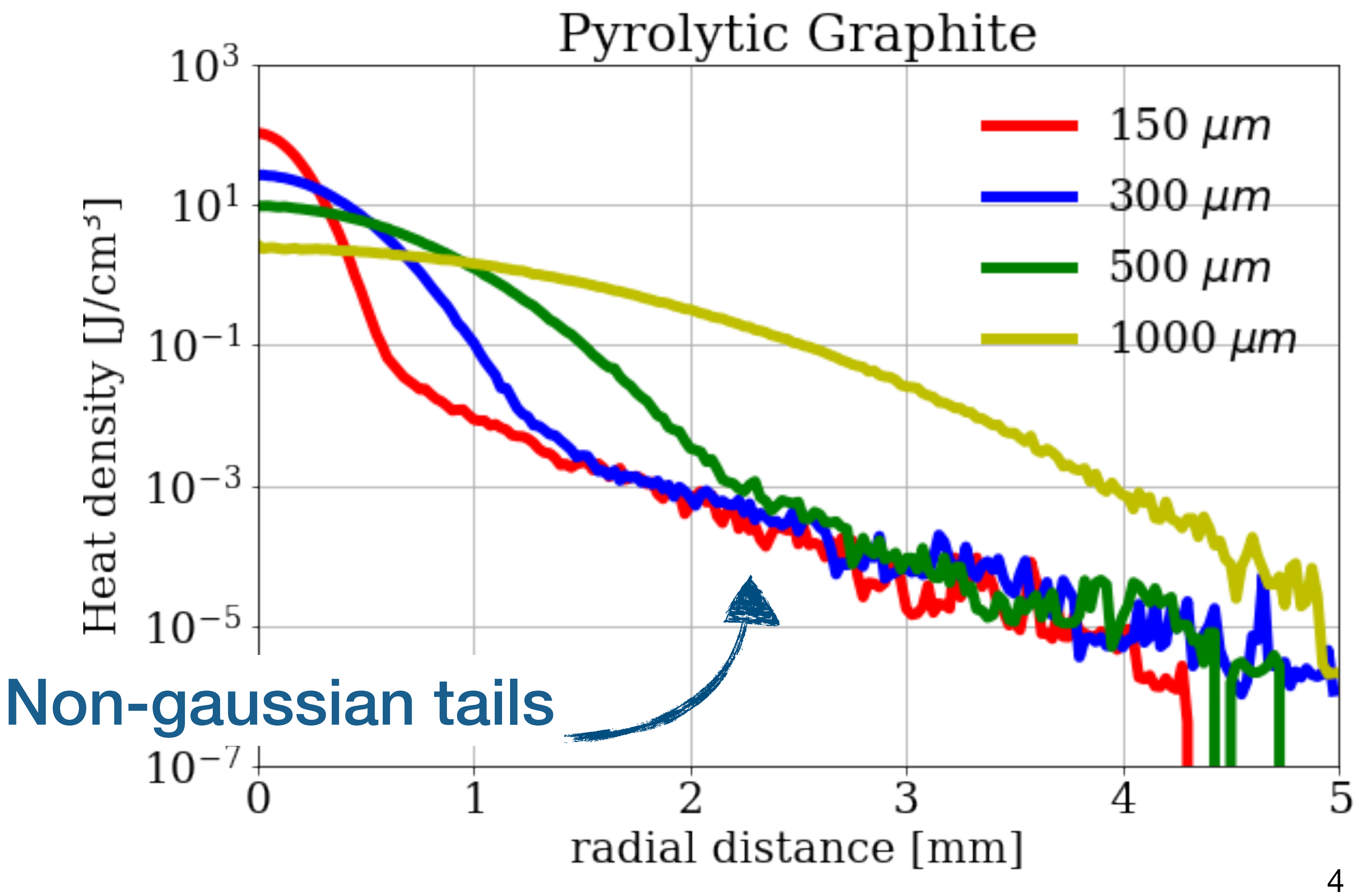

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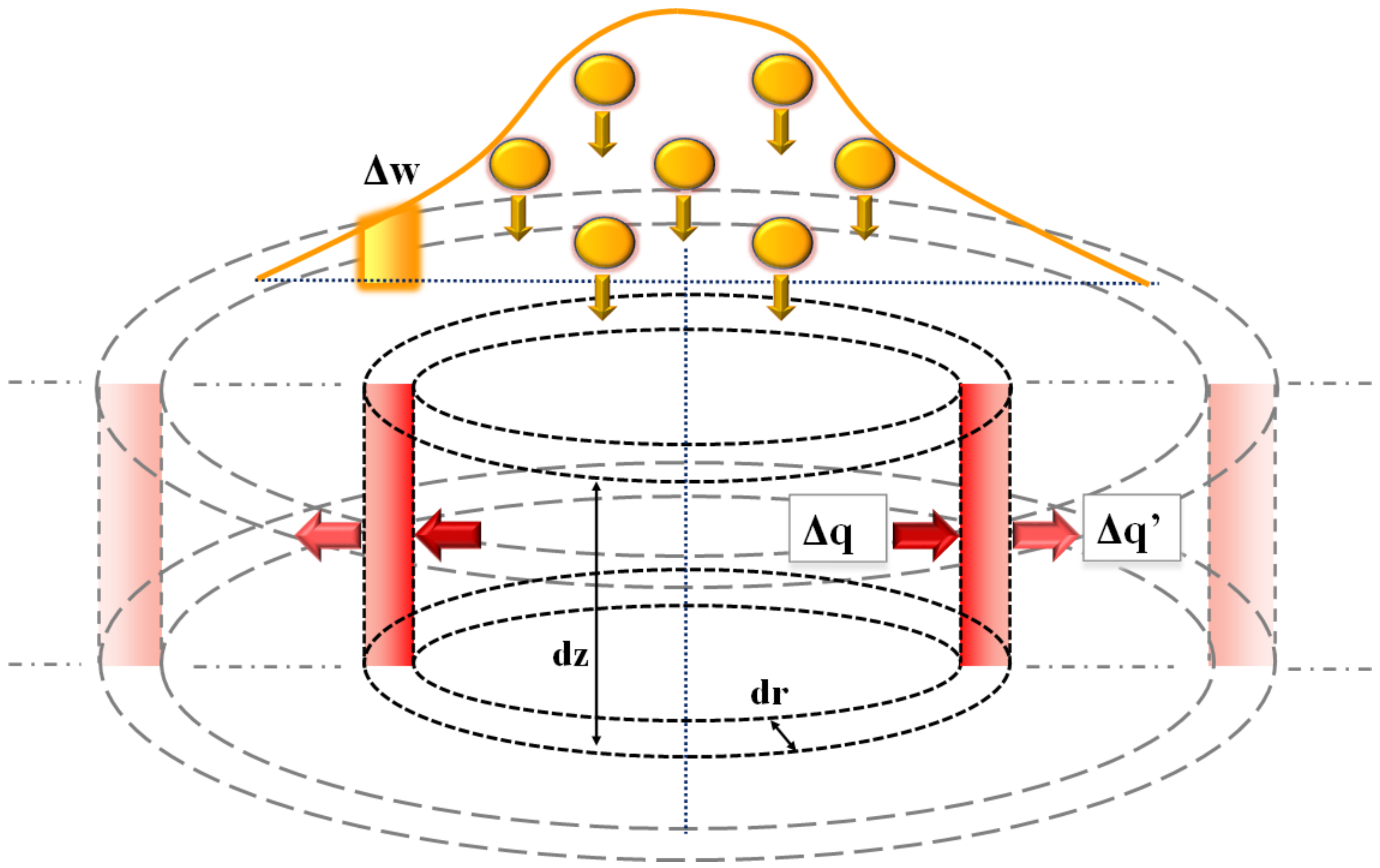
THEORETICAL MODELLING FOR THERMAL EVOLUTION



- Splitting target volume in voxels profiting from axial symmetry
- From energy deposition, simulate diffusion and radiation evolution with Finite-difference time-domain (FDTD) method

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k: therm. conductivity
ρ: density
c_p: spec. heat
F_O: Fourier number
D: therm. diffusivity
L: ch. length
P_{cw}: dissipated power
S: target surface
$C_{max,a}$: peak dep. E
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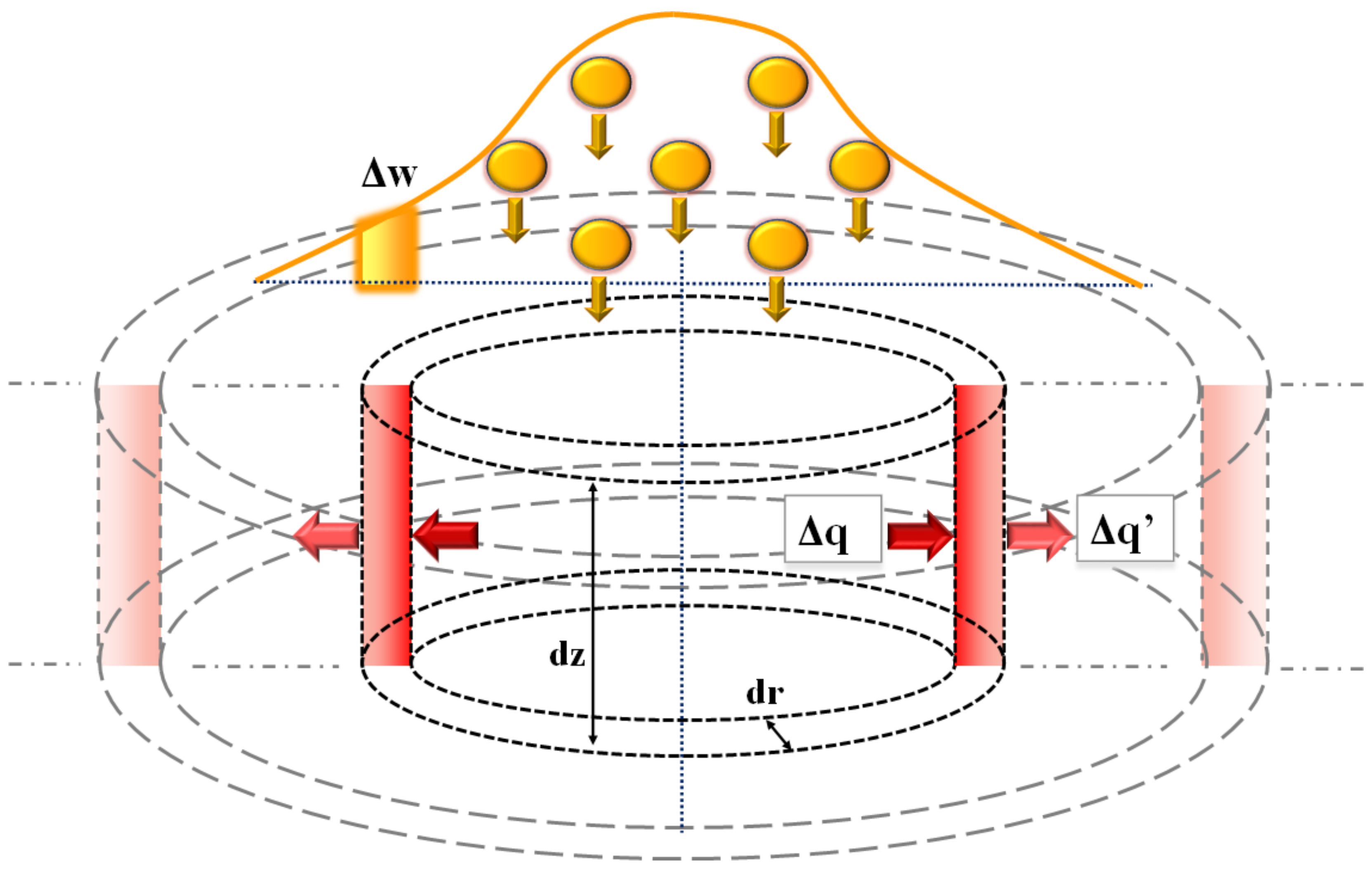

Every single bunch

$$\nabla \cdot (-k \cdot \nabla T) + dR = \rho c_p \frac{\partial T}{\partial t}$$

numerical heat transfer convergence for Fourier number F_O satisfying:

$$F_O = \frac{D\Delta t}{L^2} \leq \frac{1}{2} \quad \Rightarrow \quad \Delta t \leq \frac{\min(\Delta r^2, \Delta z^2)}{2D_{\max}}$$

define a set of differential equations for T evolution

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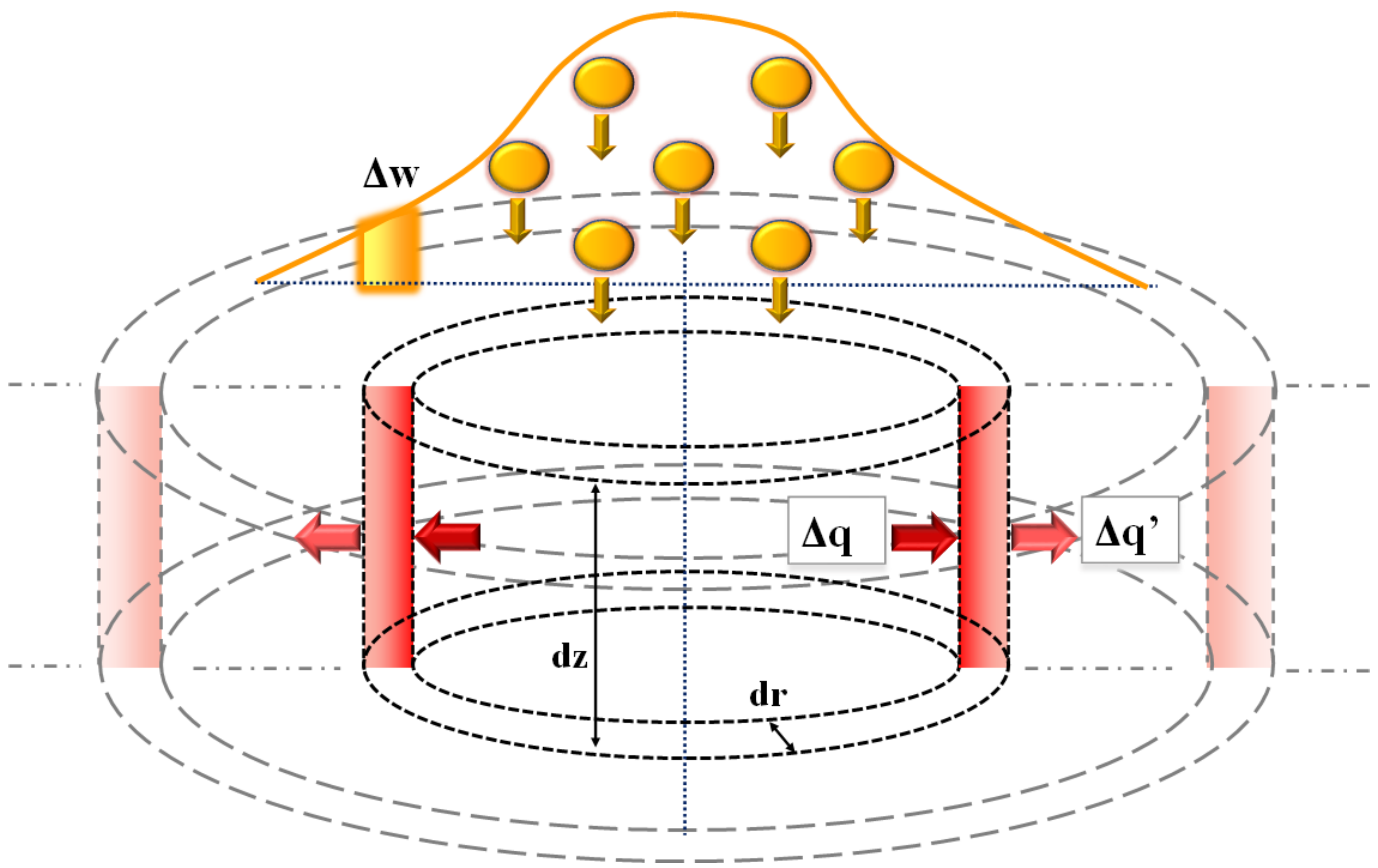

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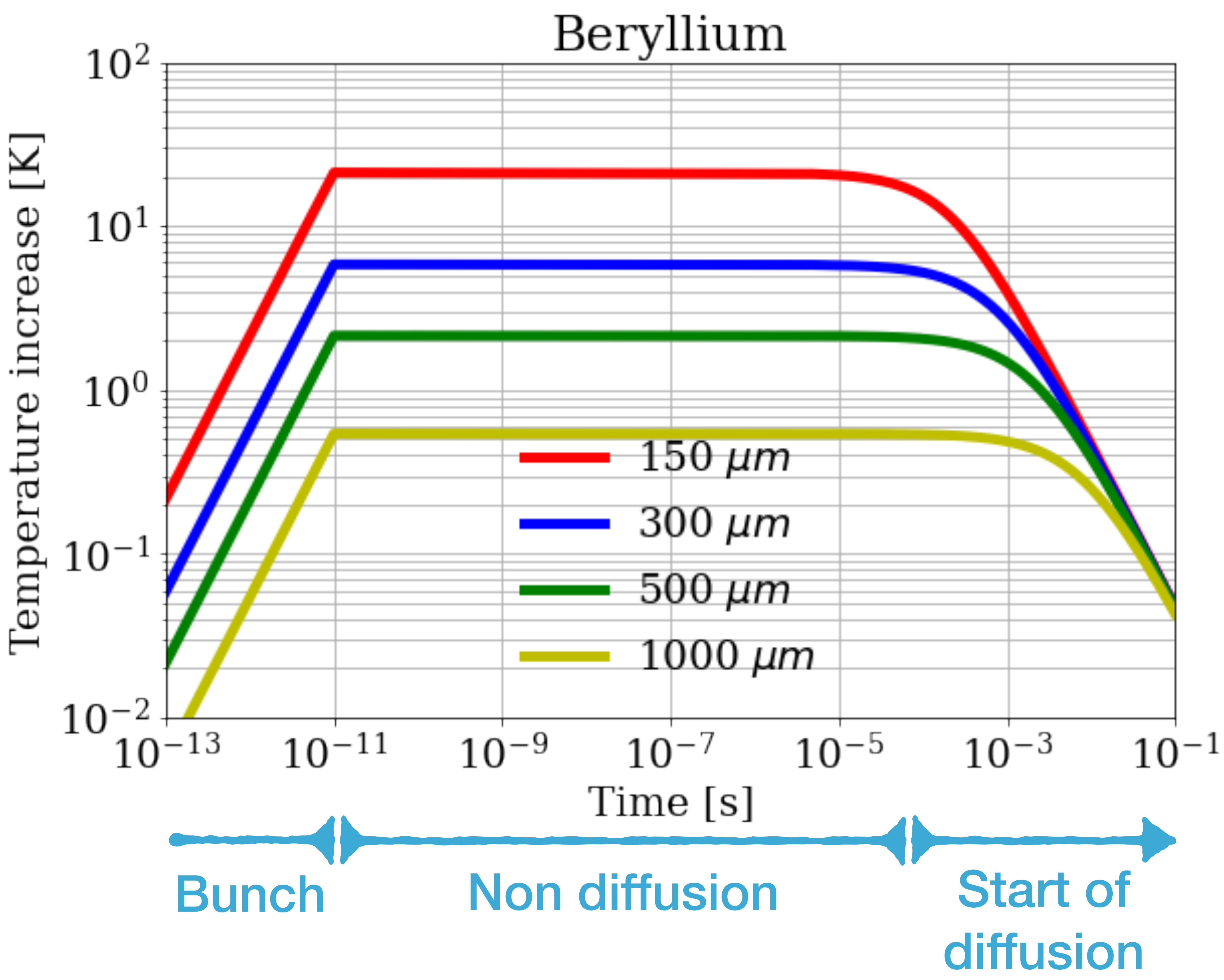
Target radiation in Steady-state regime

$$P_{cw} = \epsilon\sigma\left(T^4 - T^4_{room}\right) S = mc_p \frac{\partial T}{\partial t}$$

$$\Delta T = \sqrt{T^4_{amb} + \left(\frac{a^2 \cdot L}{r^2 + r \cdot L}\right) \frac{C_{max,a} \cdot N_{part \cdot N_{pulses}}}{\epsilon \cdot \sigma_B \cdot T_{rep}}} - T_{amb}$$

HEAT TIME EVOLUTION

Single bunch on the target



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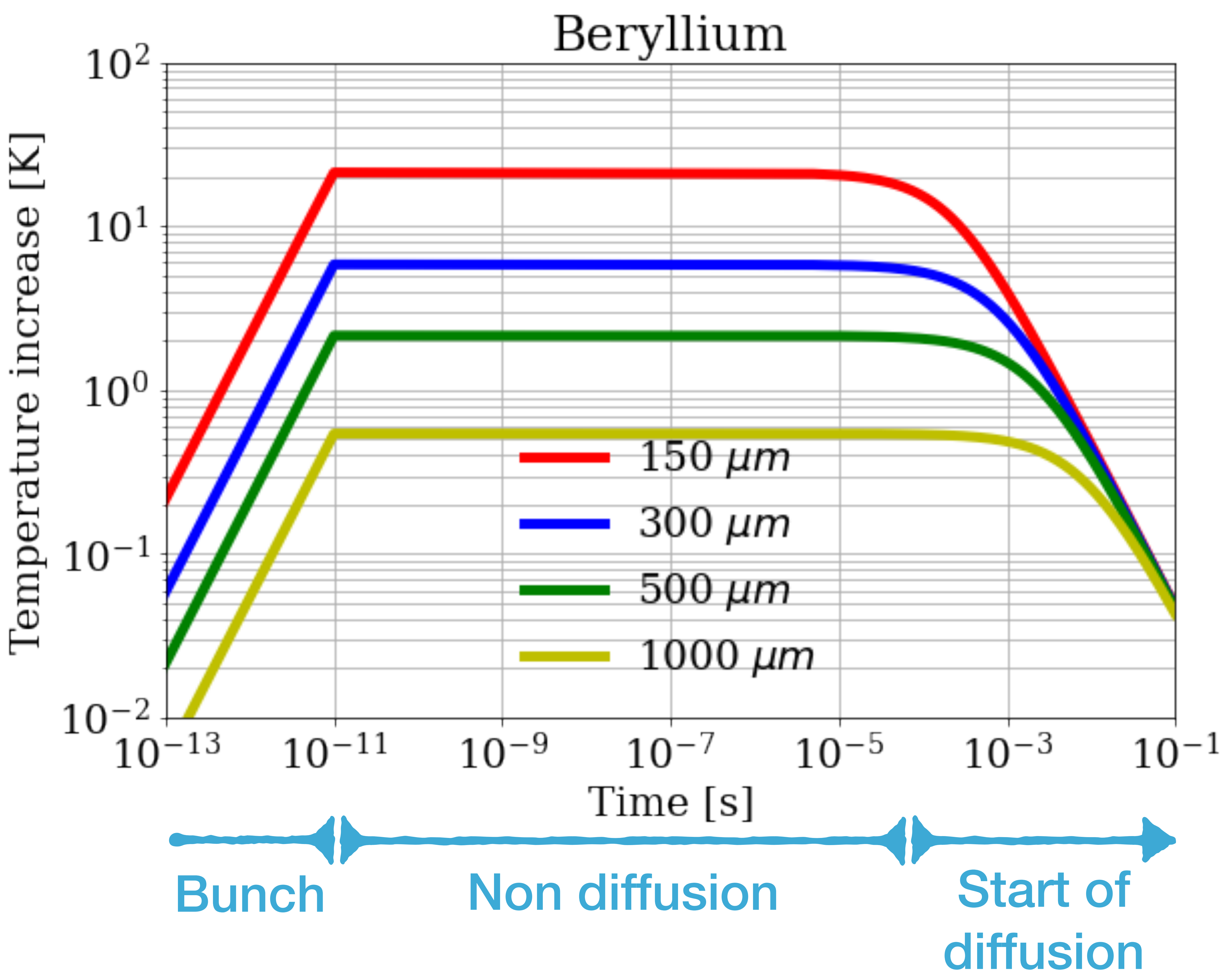
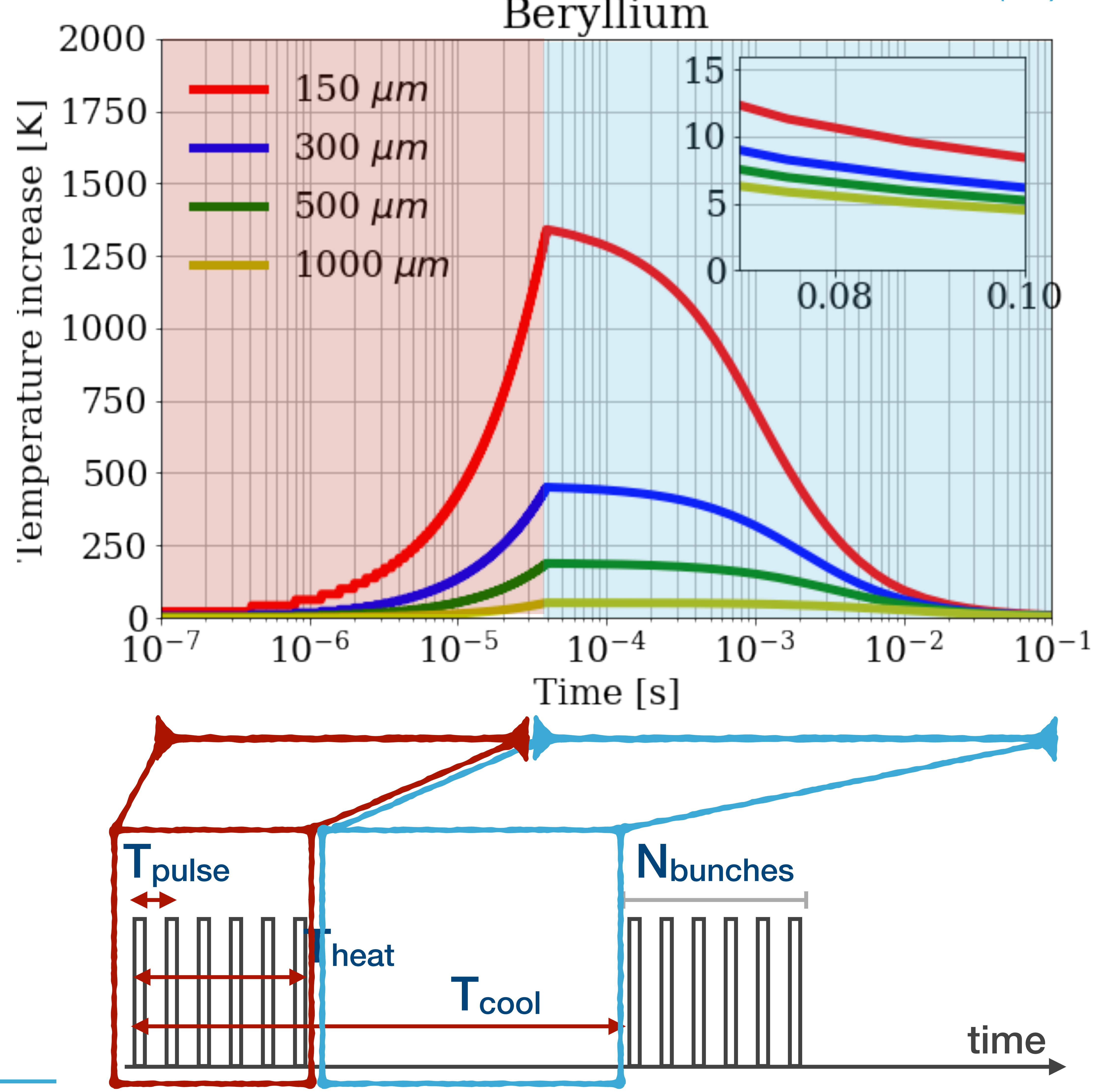


Train of 100 bunches

$T_{Melt}(Be) \sim 1300\ K$



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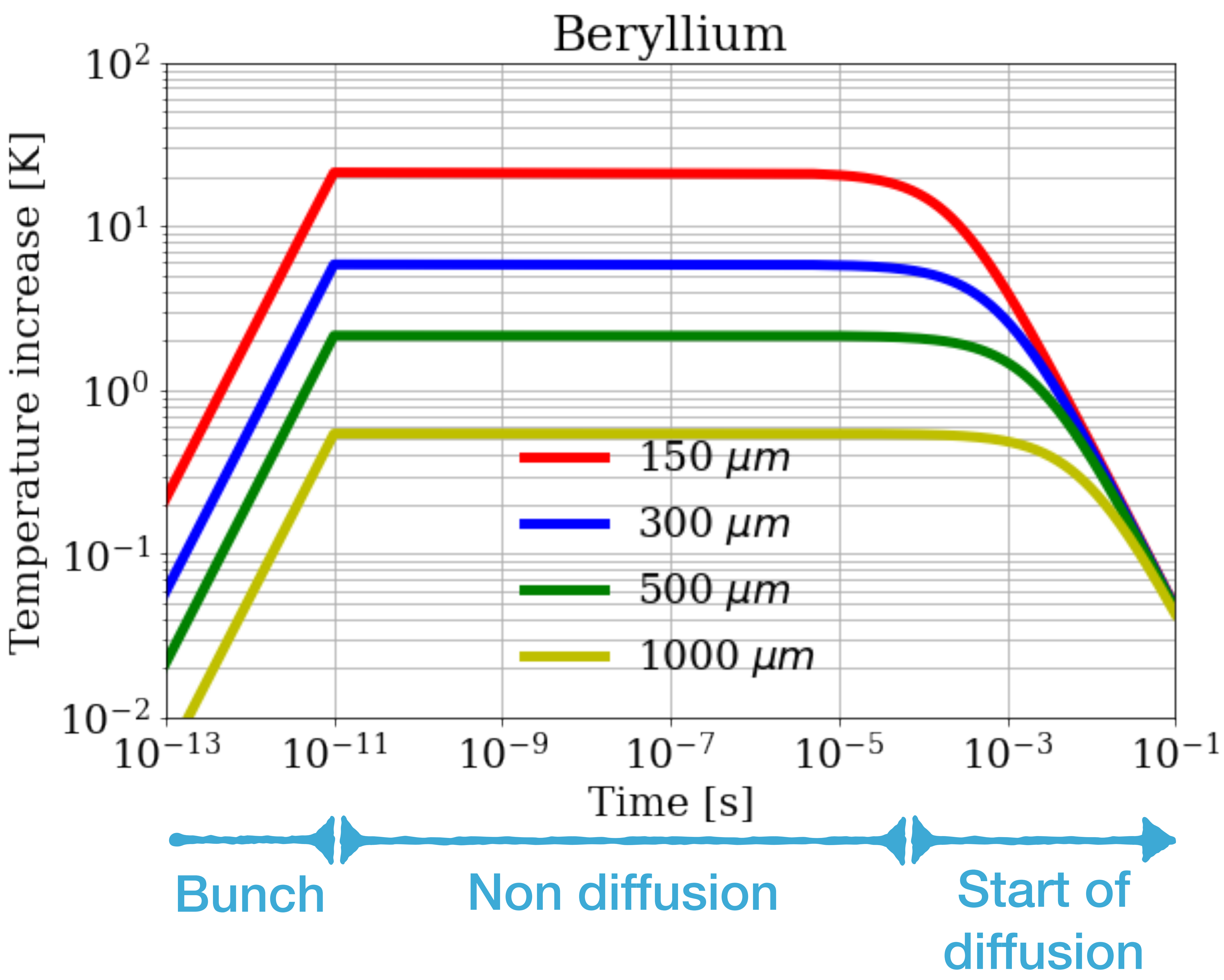

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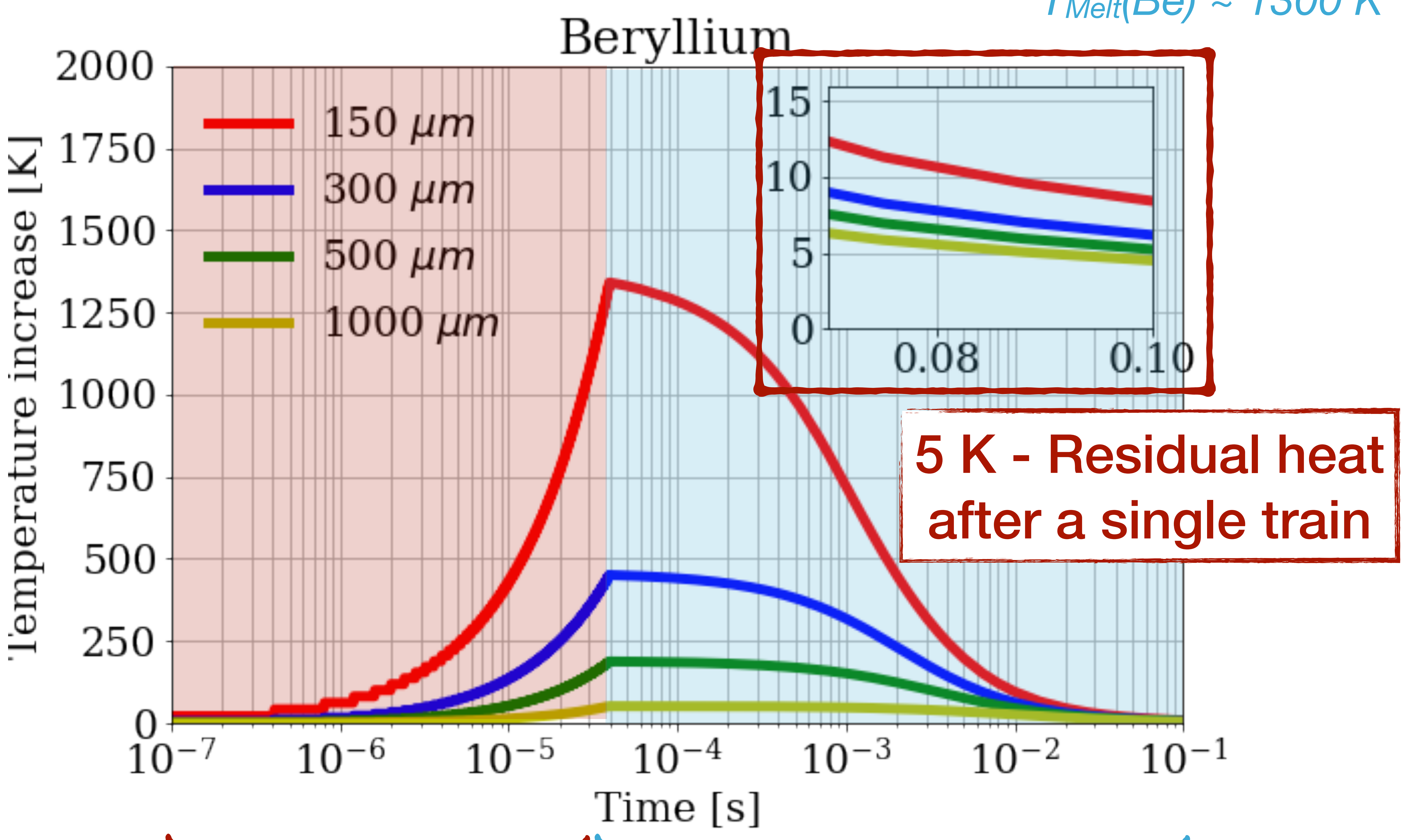
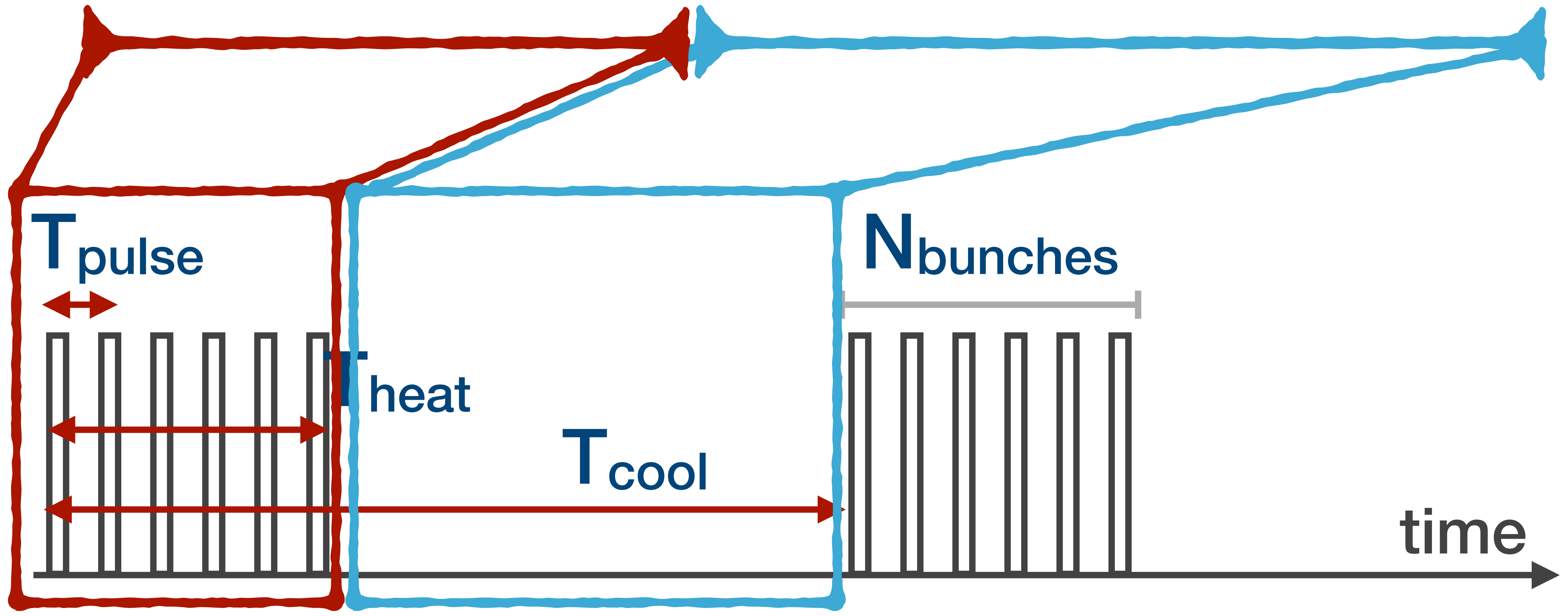
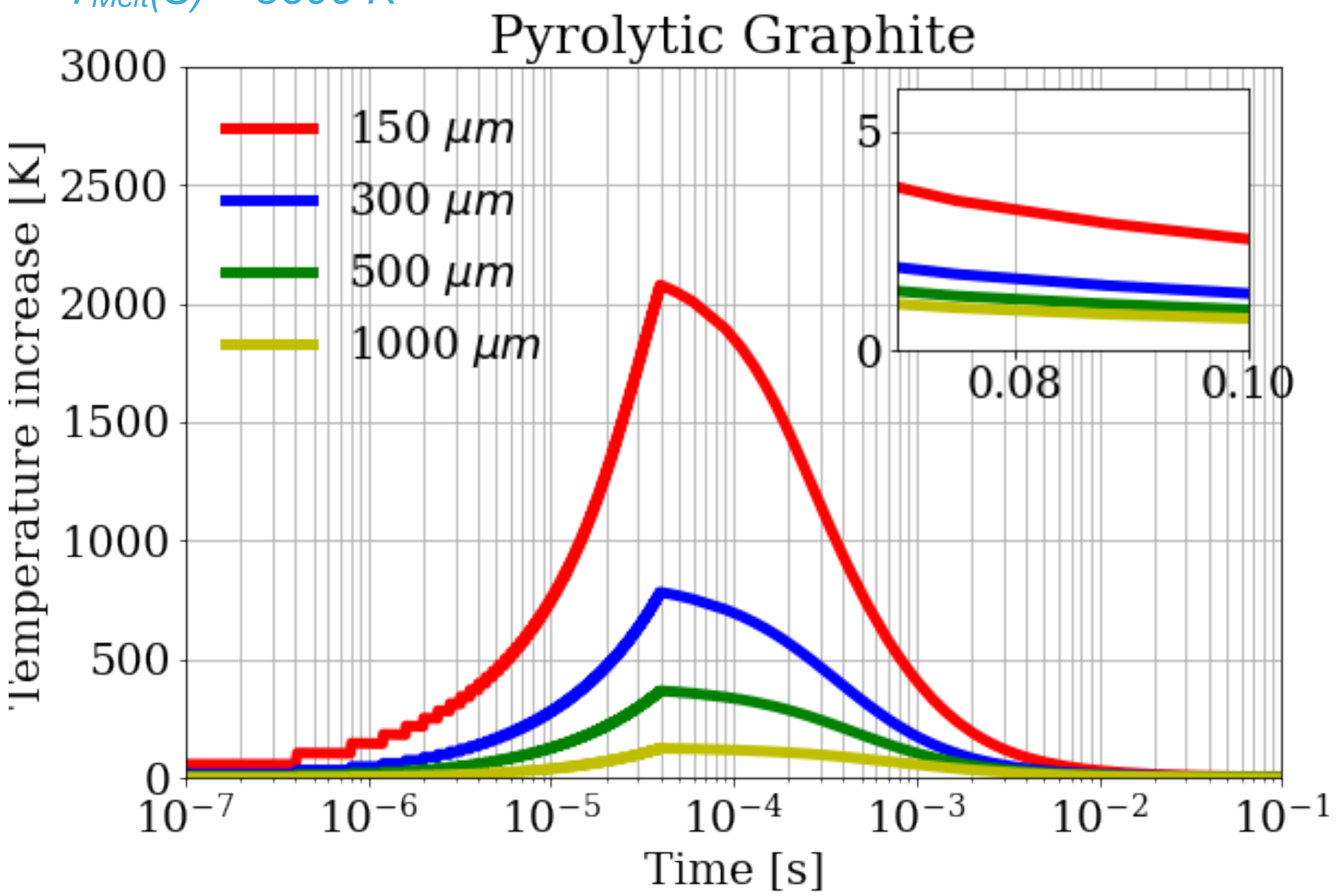




TARGET TEMPERATURE RISE

- Pyrolytic Graphite (C) reaches higher temperature but has higher melting point

T_{Melt}(C) ~ 3600 K



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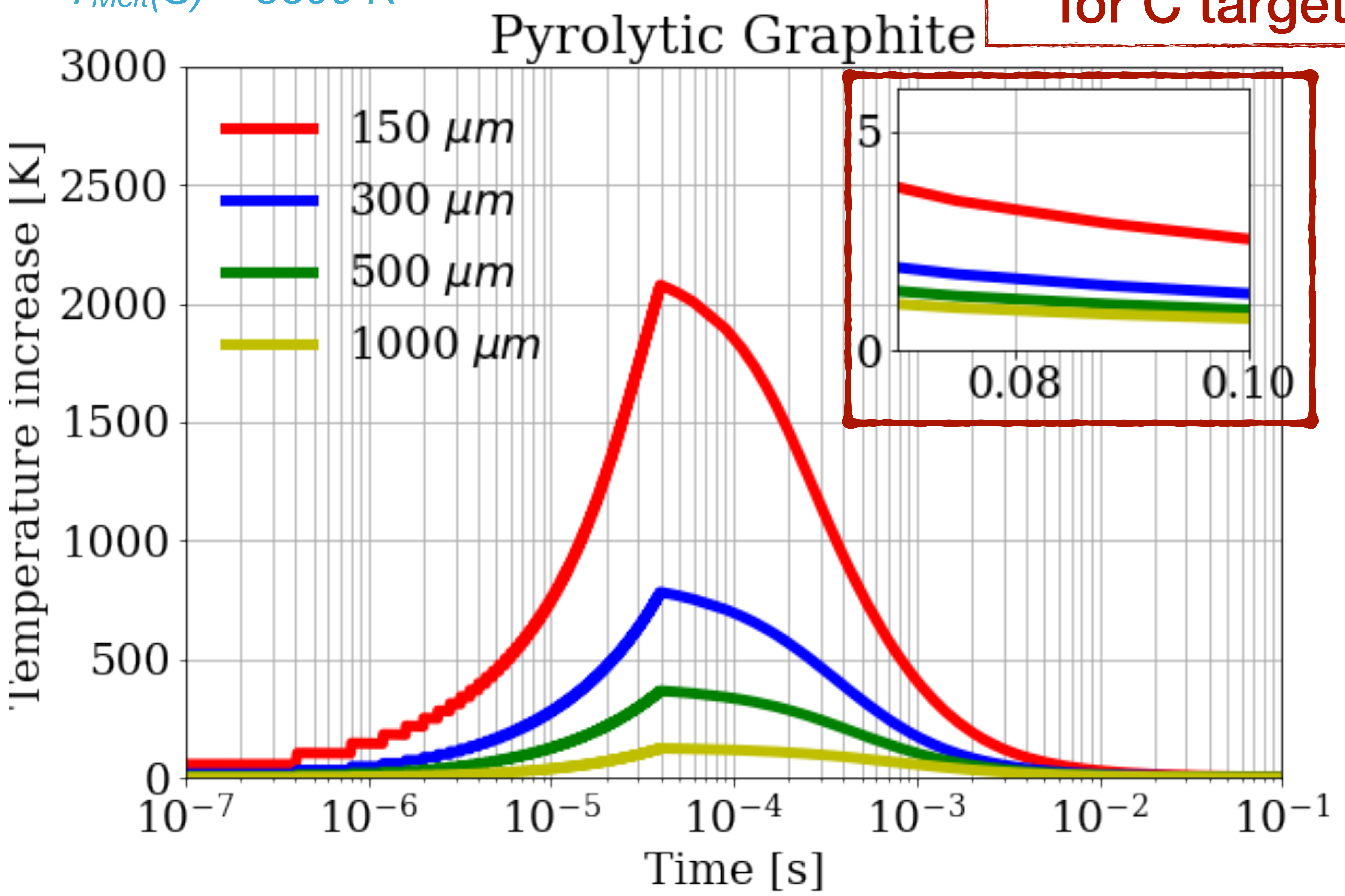
Smaller residual heat for C target (1 K)



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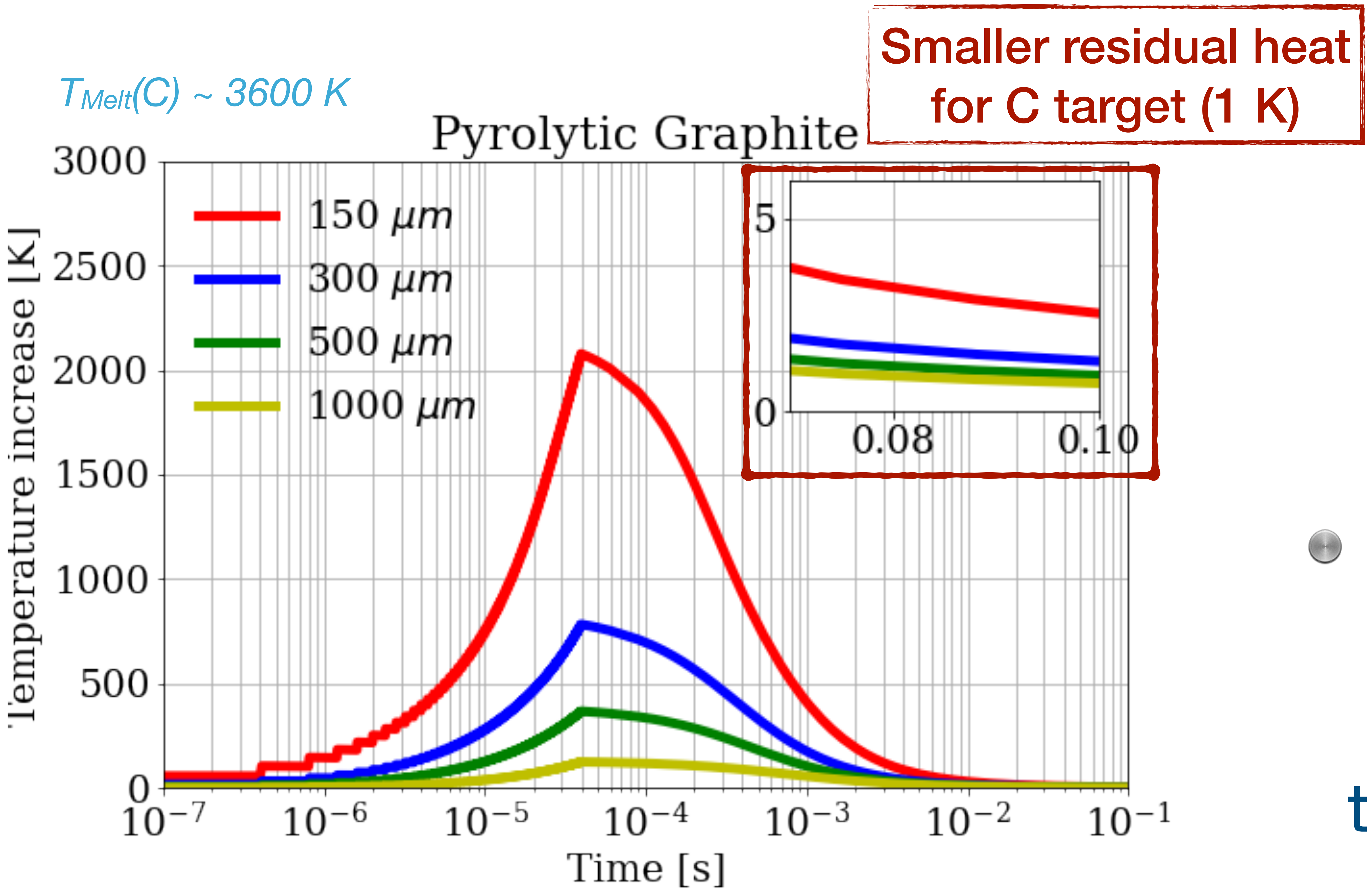
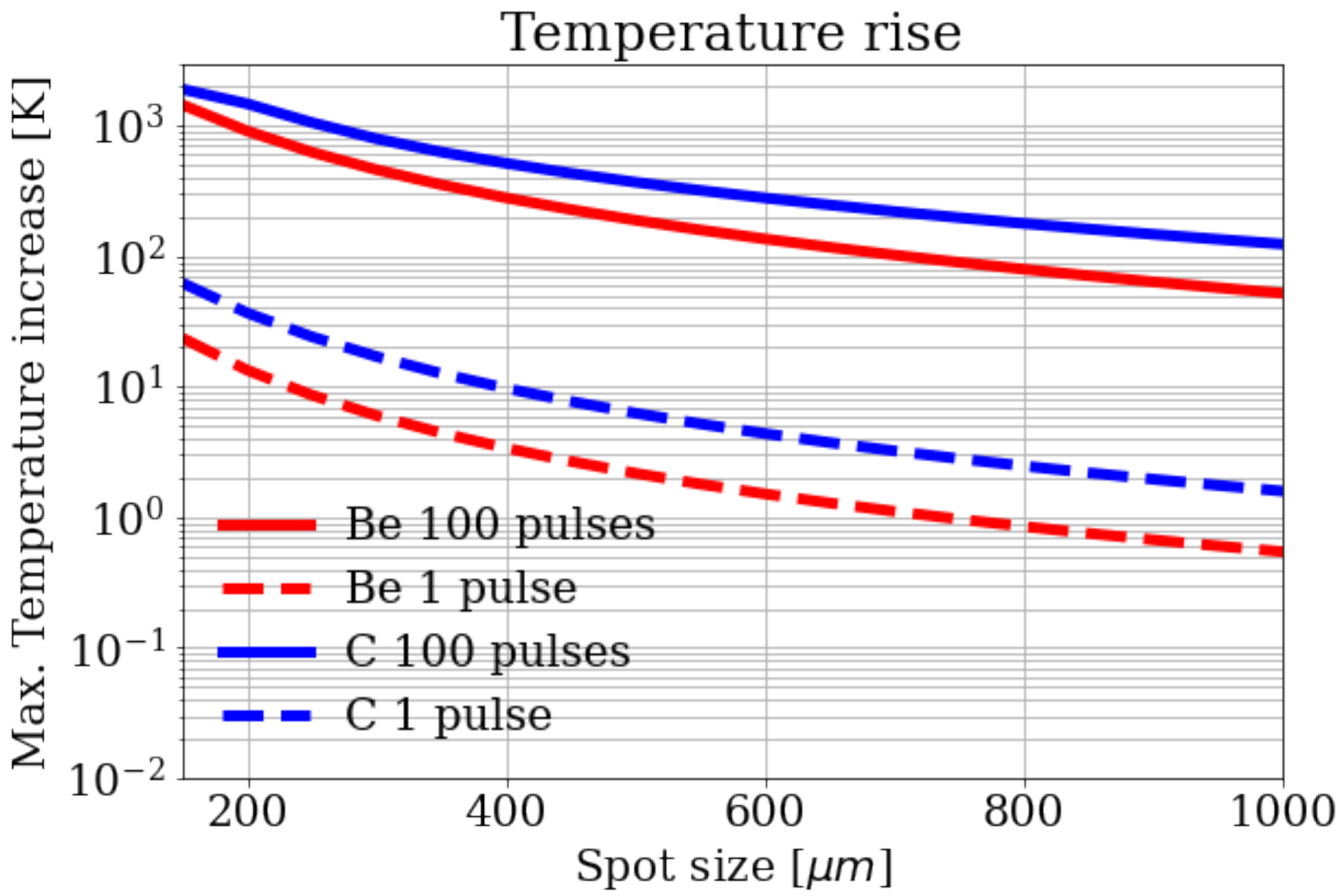
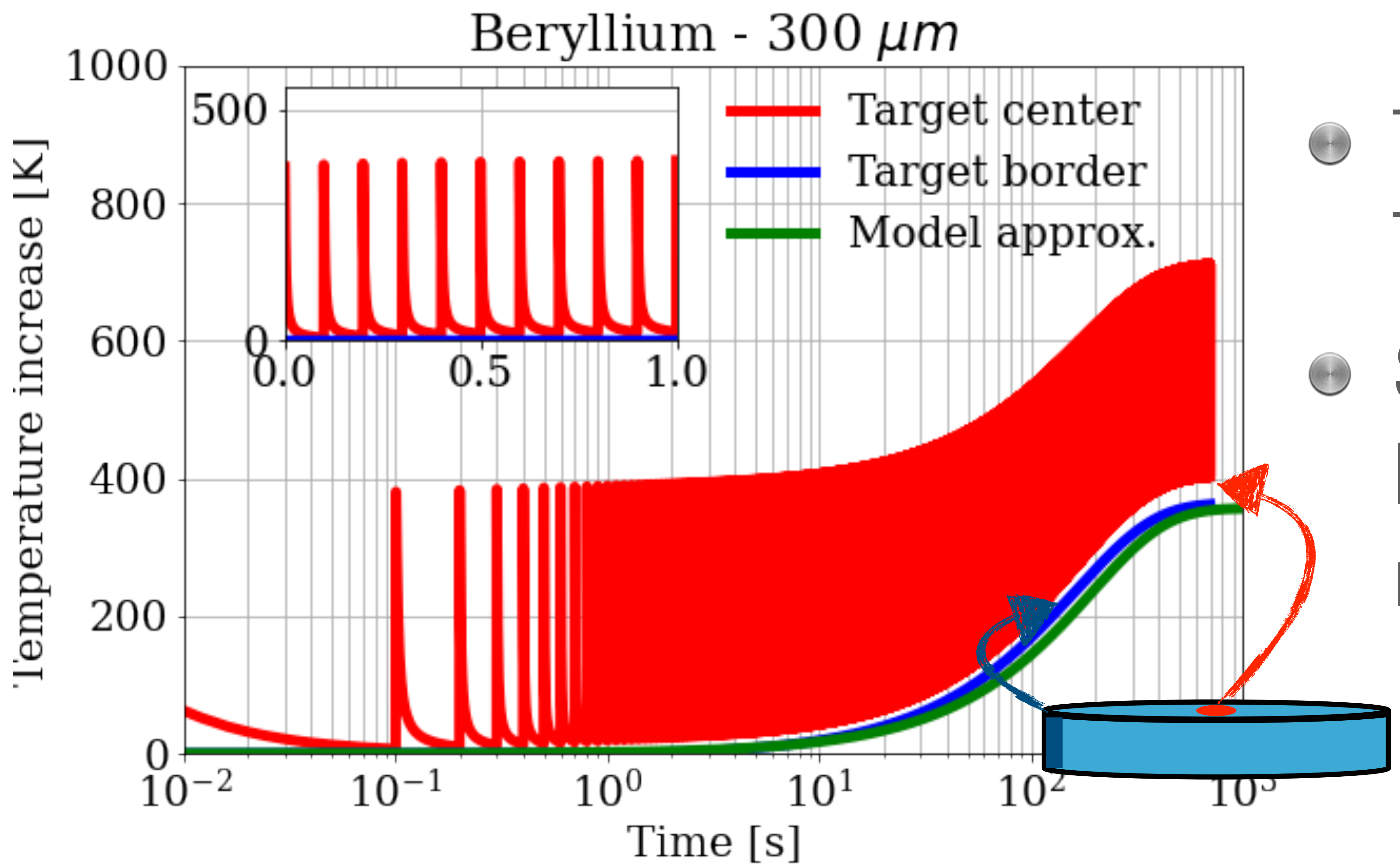


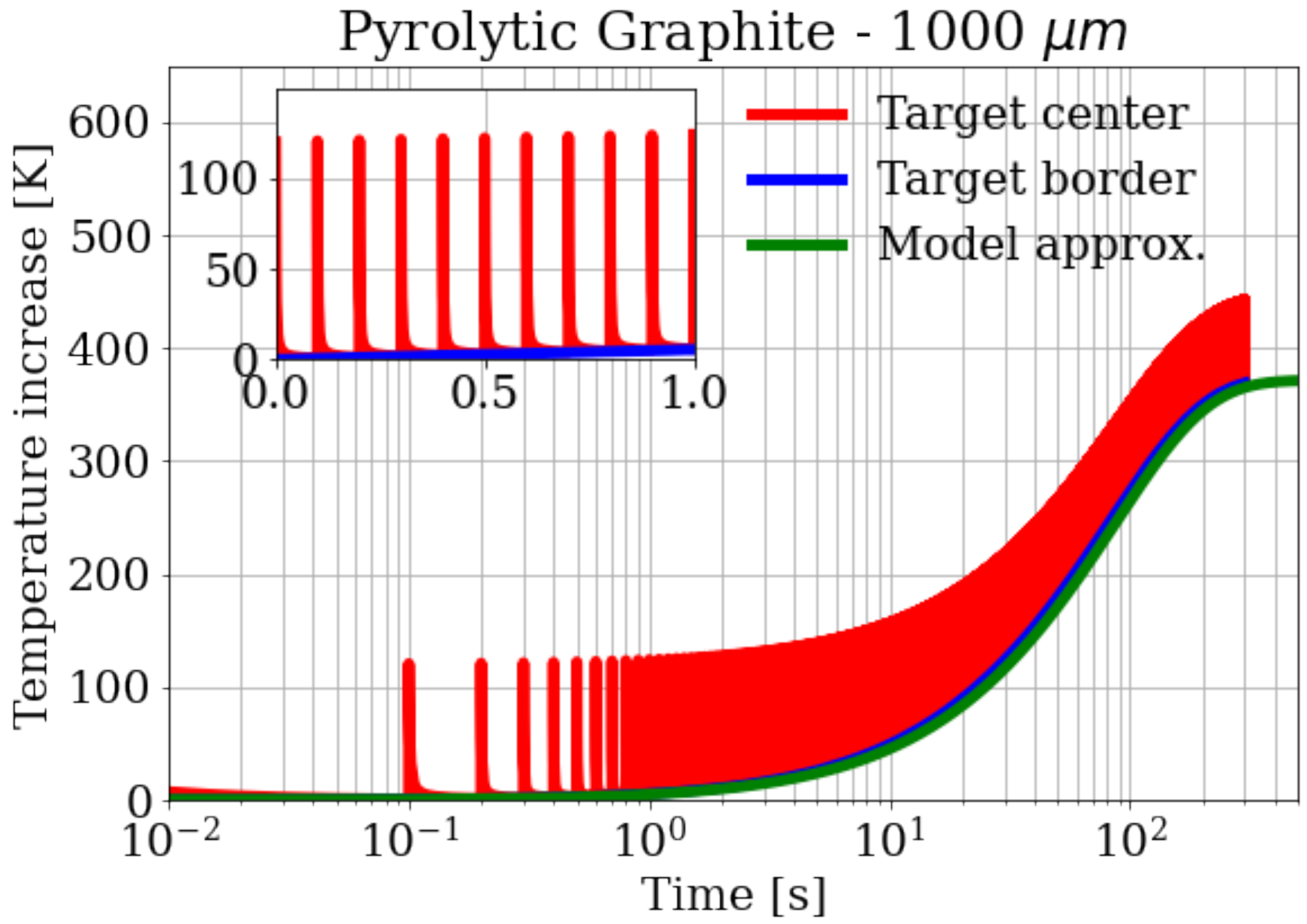


- Temperature reached after 100 pulses is smaller than 100x that reached after a single pulse:

though small, a diffusion process starts before the end of the train!

MULTI-TRAIN HEATING AND STEADY-STATE REGIME





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Simulations for R=2.5 cm due to computational limits

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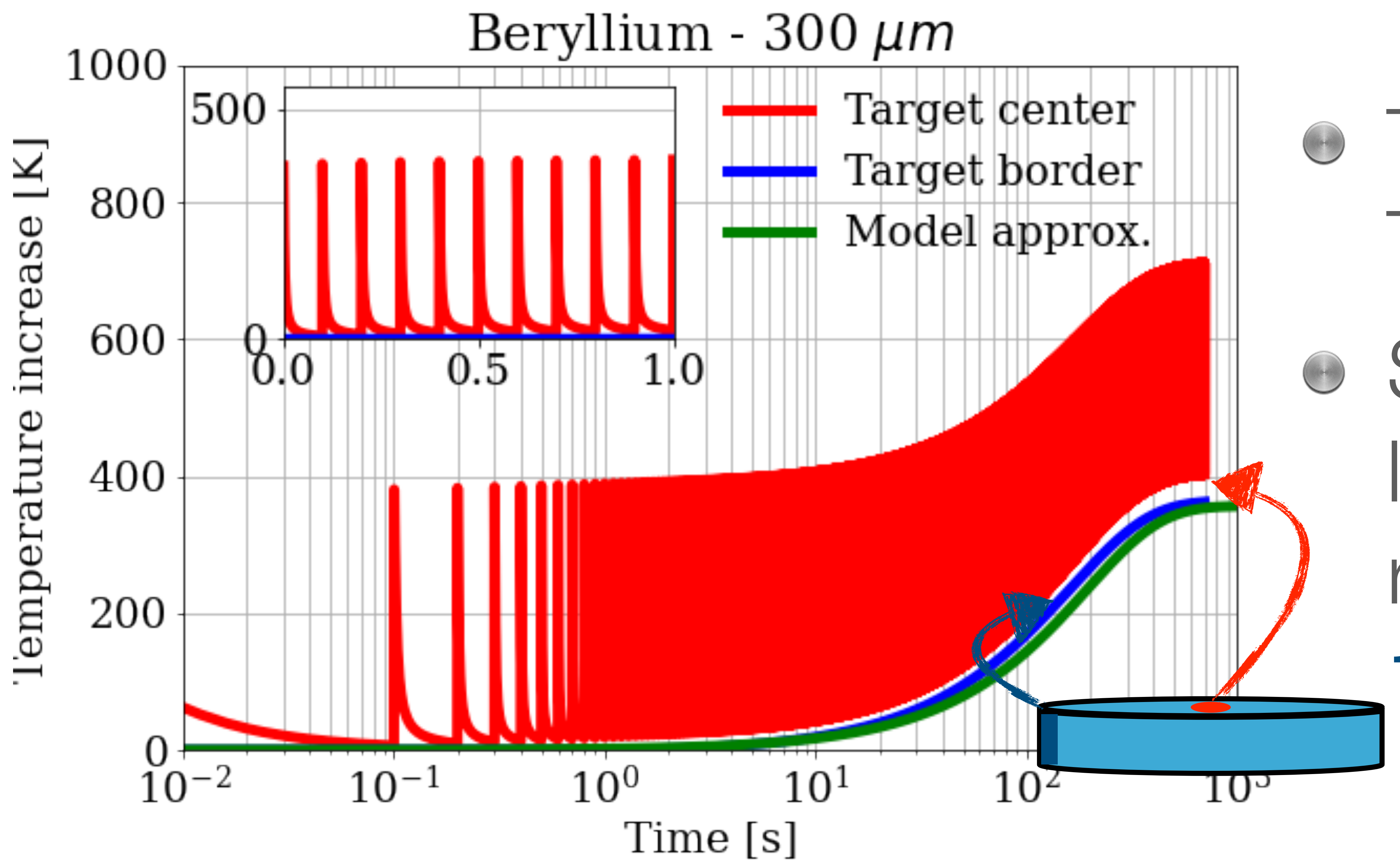

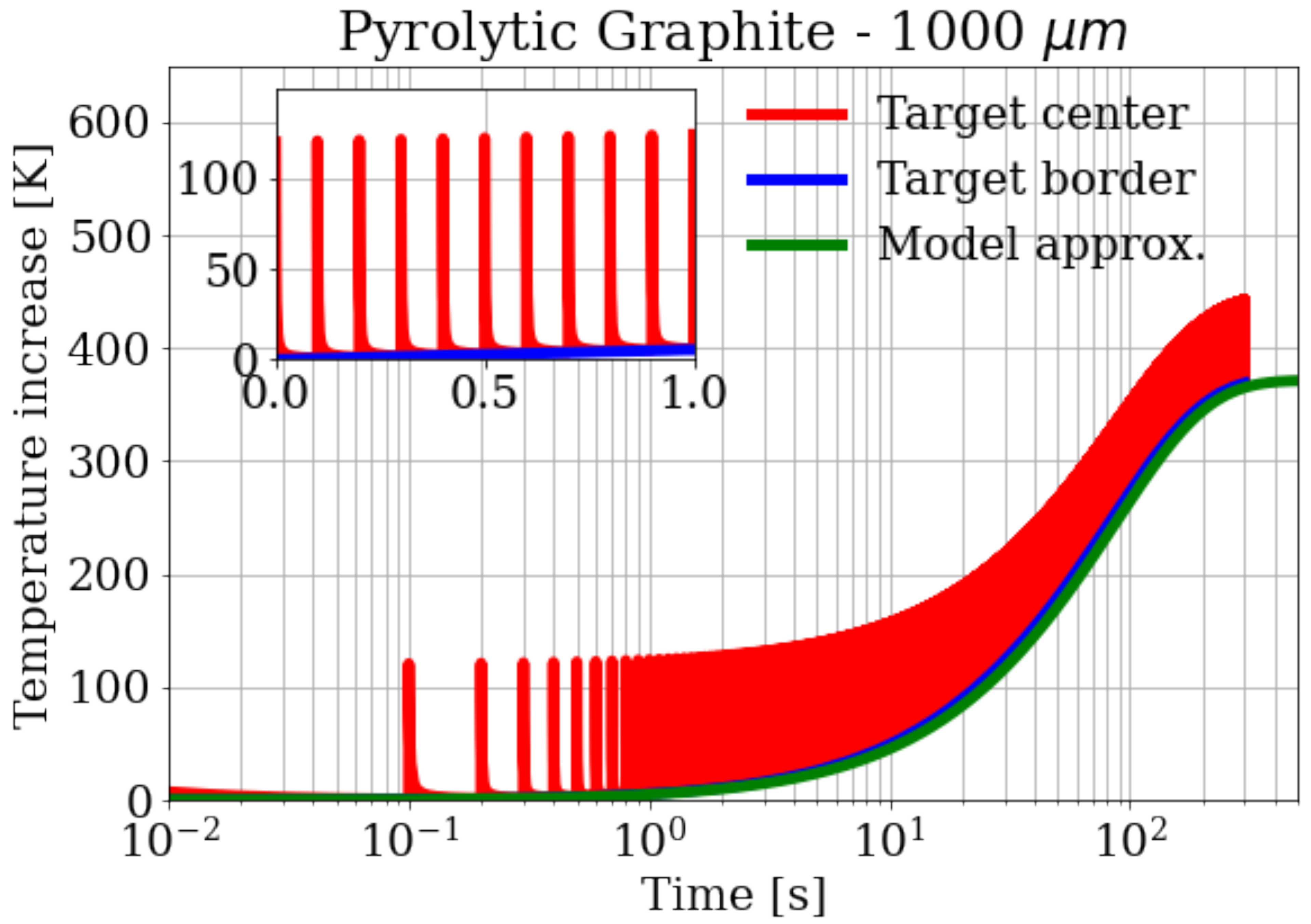

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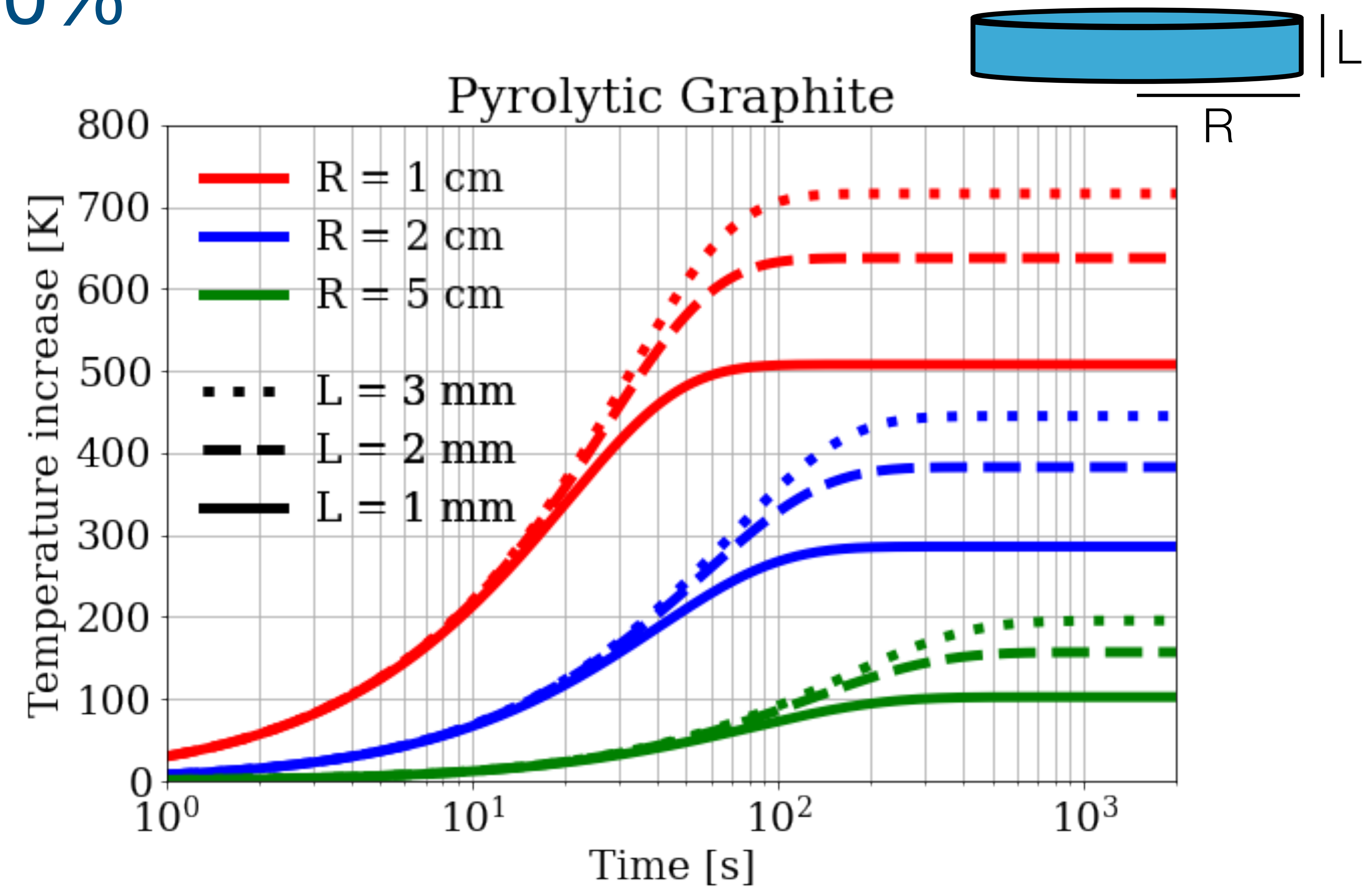


Allows target design optimisation

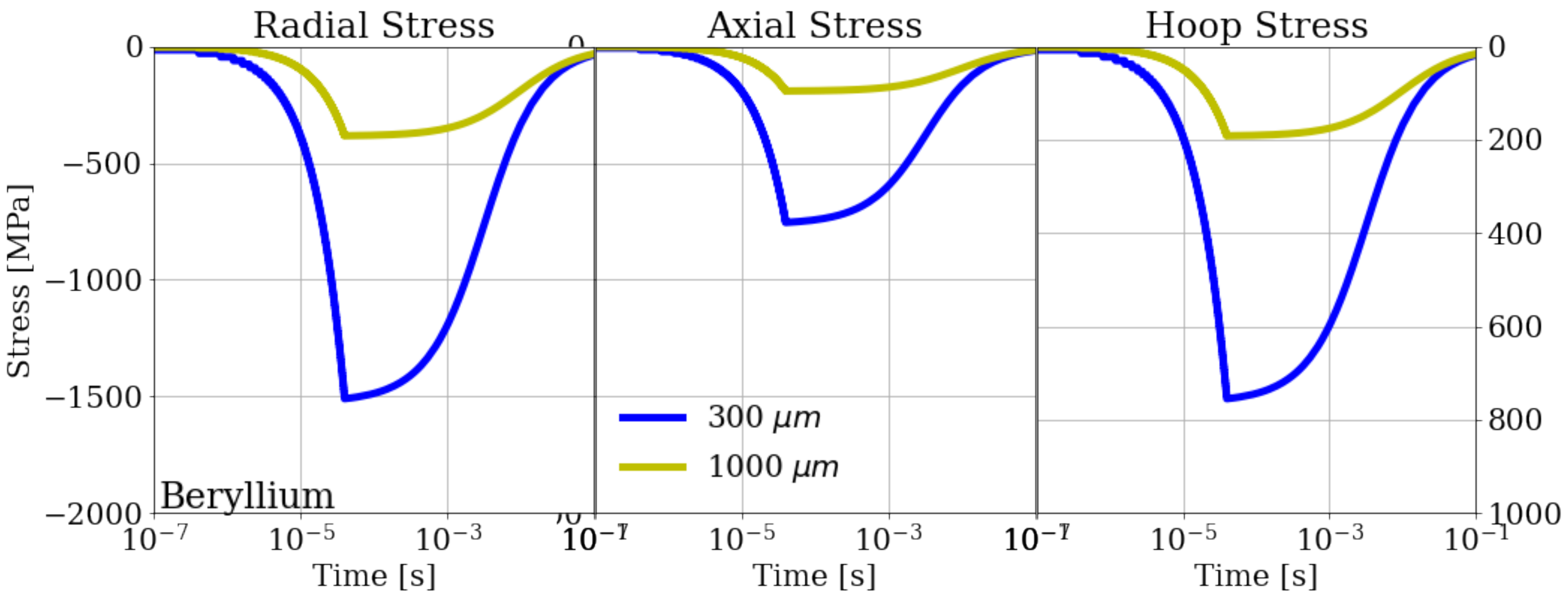
TARGET THERMOMECHANICAL STRESSES

- Evaluate thermomechanical stresses due to material thermal gradients
- Axially unrestrained plane strain, assuming a constant axial strain

$$\sigma_{rr} = \frac{E}{1-\nu}\left[\frac{1}{R^2}\int_0^R \alpha\theta(r,t)r\,dr - \frac{1}{r^2}\int_0^r \alpha\theta(r,t)r\,dr\right]$$ Radial Stress

$$\sigma_{zz} = \frac{E}{1-\nu}\left[\frac{2}{R^2}\int_0^R \alpha\theta(r,t)r\,dr - \alpha\theta(r,t)\right]$$ Hoop Stress

$$\sigma_{\theta\theta} = \frac{E}{1-\nu}\left[\frac{1}{R^2}\int_0^R \alpha\theta(r,t)r\,dr - \frac{1}{r^2}\int_0^r \alpha\theta(r,t)r\,dr - \alpha\theta(r,t)\right]$$ Axial Stress



TARGET THERMOMECHANICAL STRESSES

Christensen generalised failure criterion

based on thermomechanical stresses

$$\left(\frac{1}{T}-\frac{1}{C}\right)\left(\sigma_{rr}+\sigma_{\theta\theta}+\sigma_{zz}\right)+\frac{1}{2TC}\left[(\sigma_{rr}-\sigma_{\theta\theta})^2+(\sigma_{\theta\theta}-\sigma_{zz})^2+(\sigma_{zz}-\sigma_{\theta\theta})^2\right]\leq 1$$

- Failure response depends on the target material, beam spot size and multi-pulse rate
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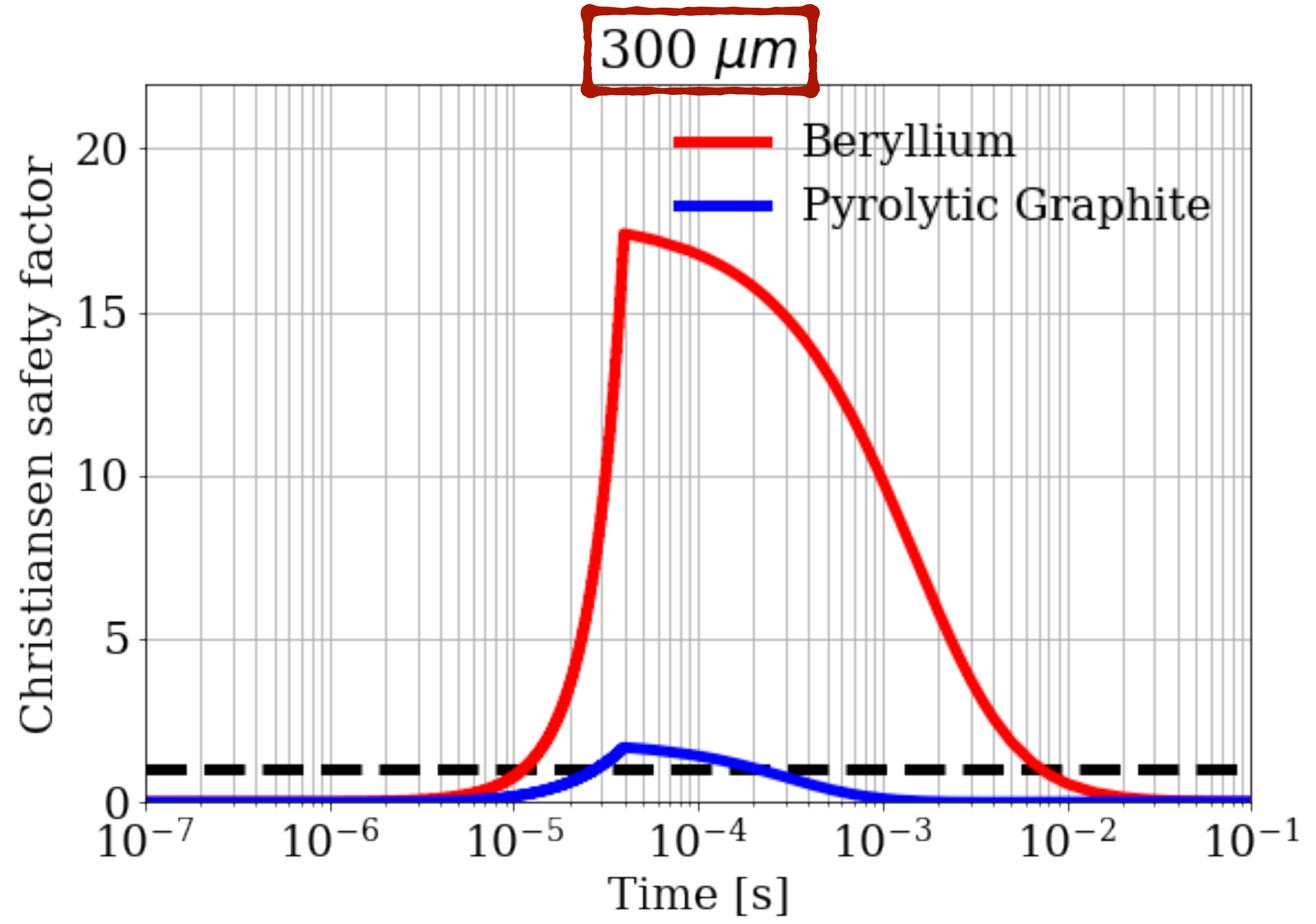
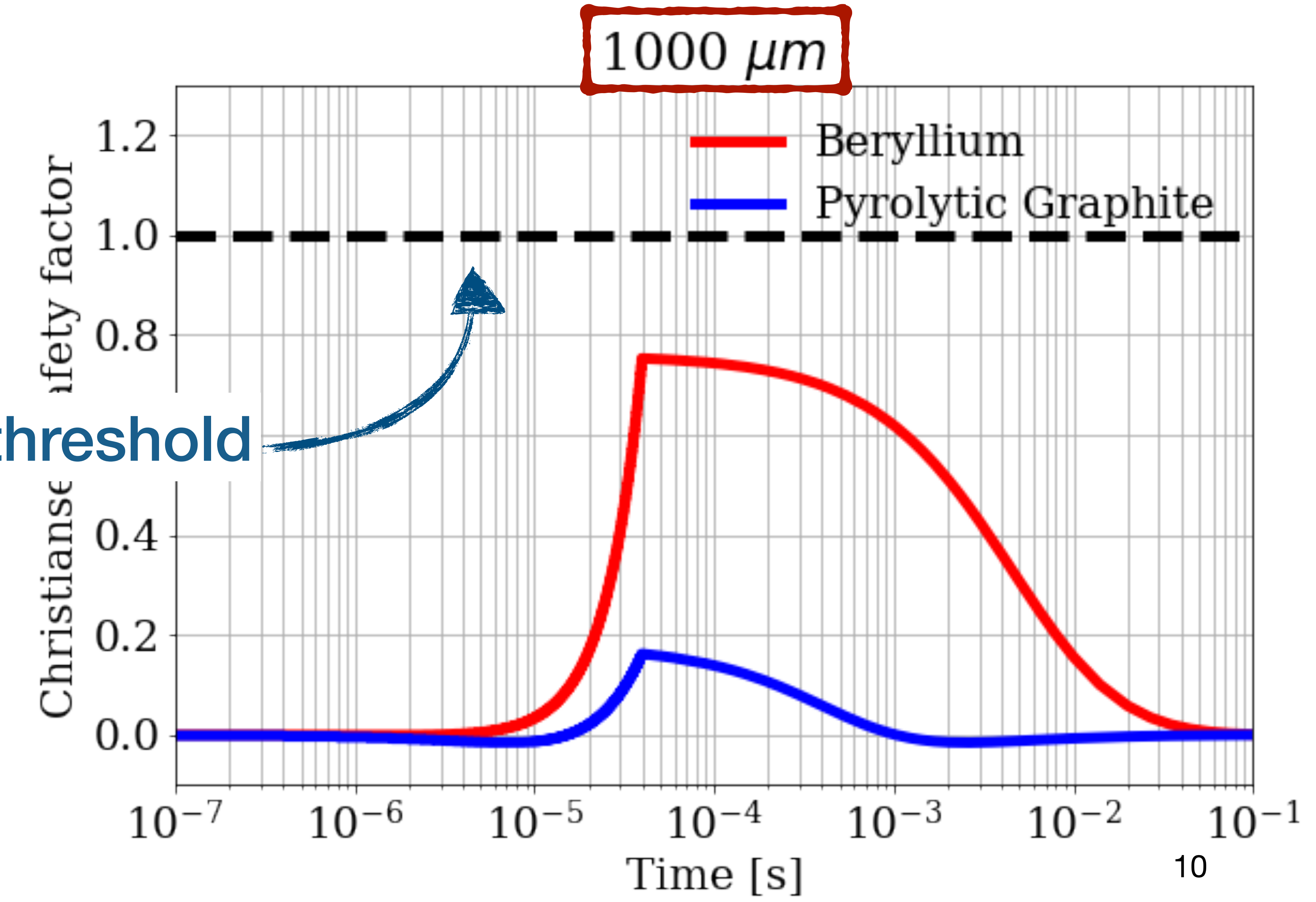
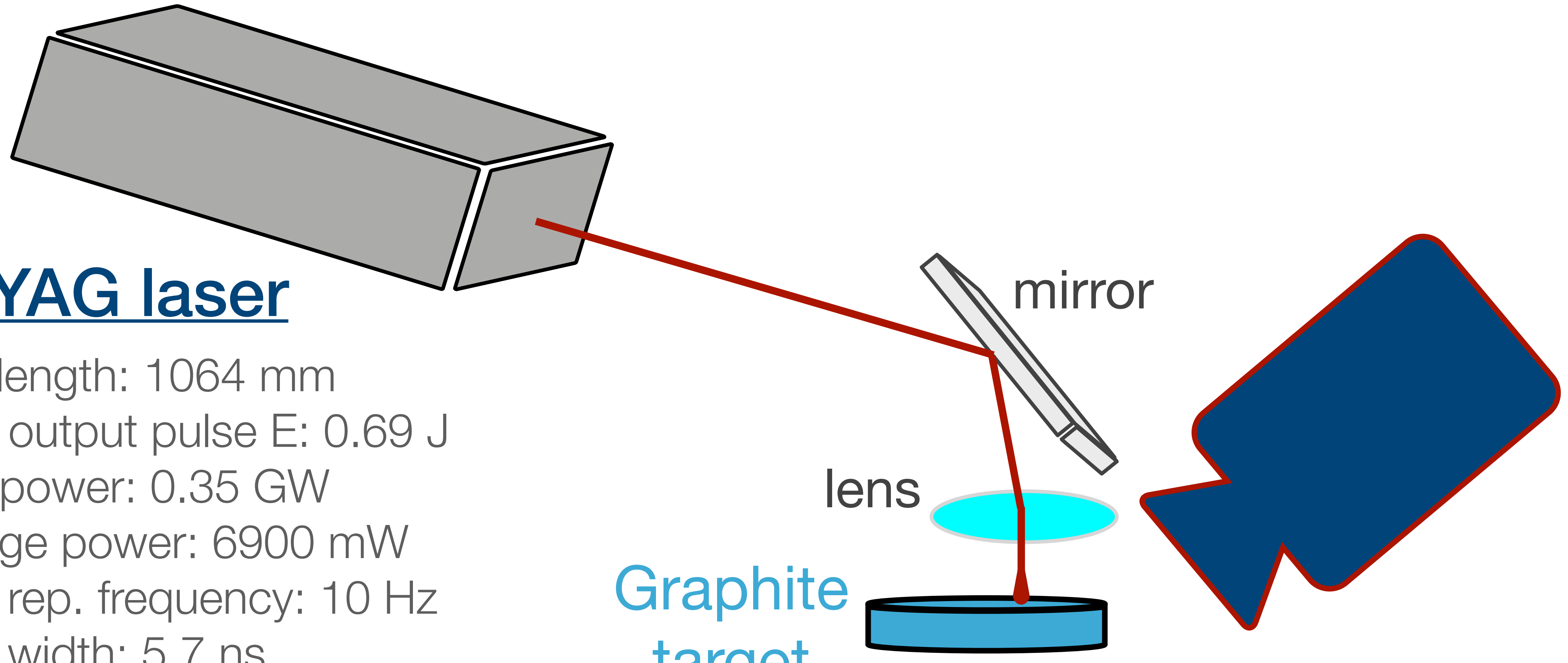




PLANNING AHEAD

Target crash test with photons

Ex ante ex post characterisation



Nd:YAG laser

Wavelength: 1064 mm
Laser output pulse E: 0.69 J
Peak power: 0.35 GW
Average power: 6900 mW
Pulse rep. frequency: 10 Hz
Pulse width: 5.7 ns

Infrared Camera
FLIR X6901sc SLS

Optic: 17 mm, calibrated in the range [-80 °C, +300 °C]

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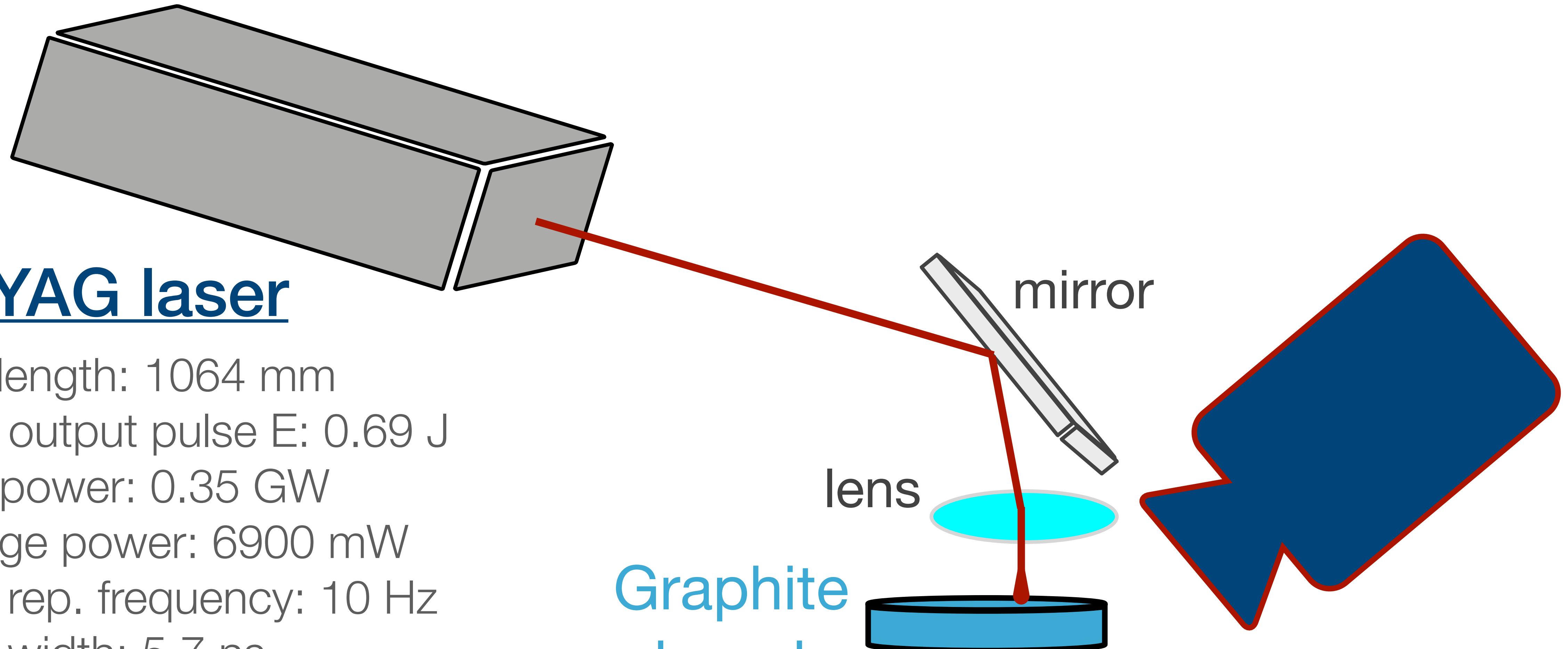

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Graphite target

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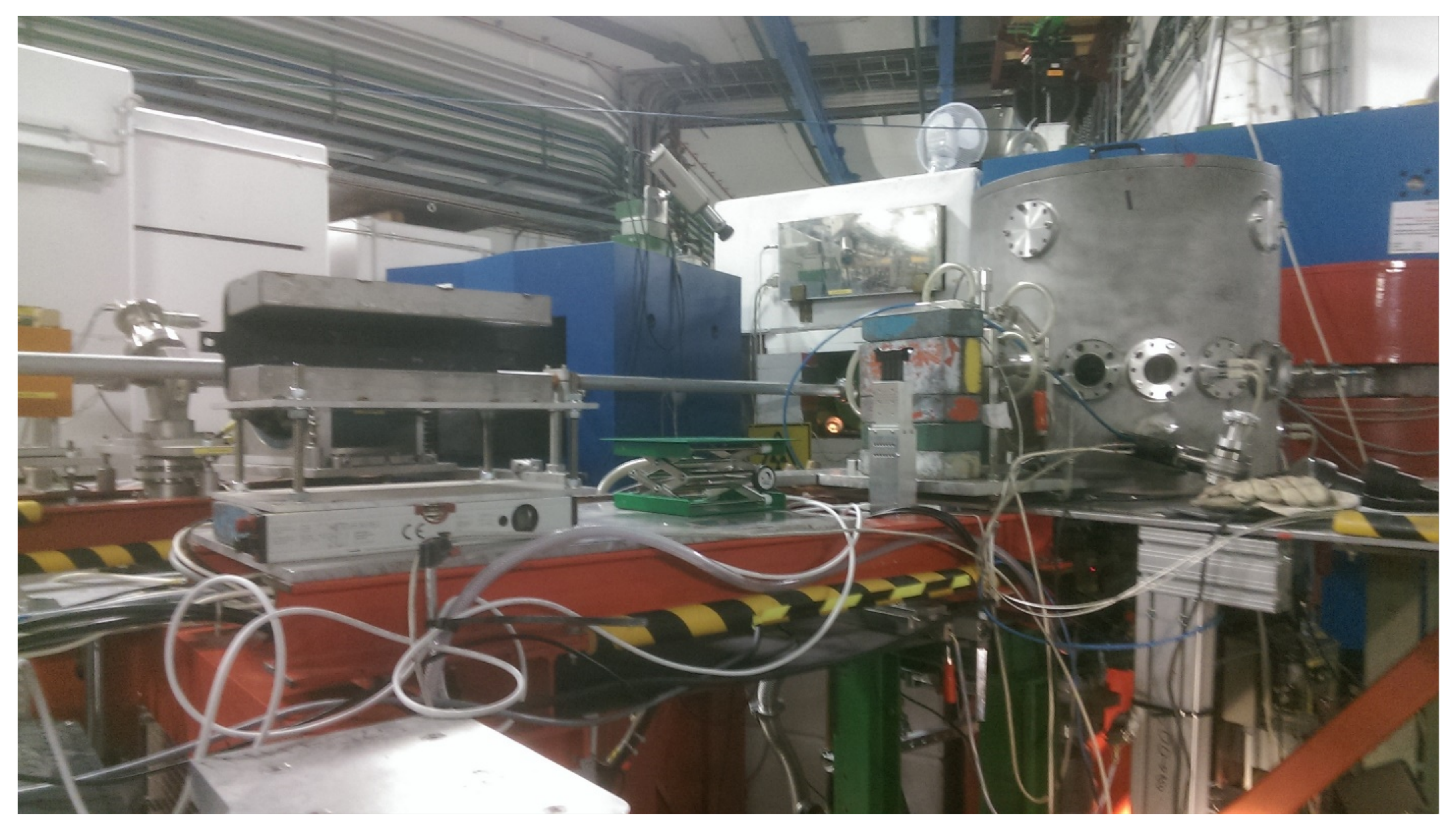
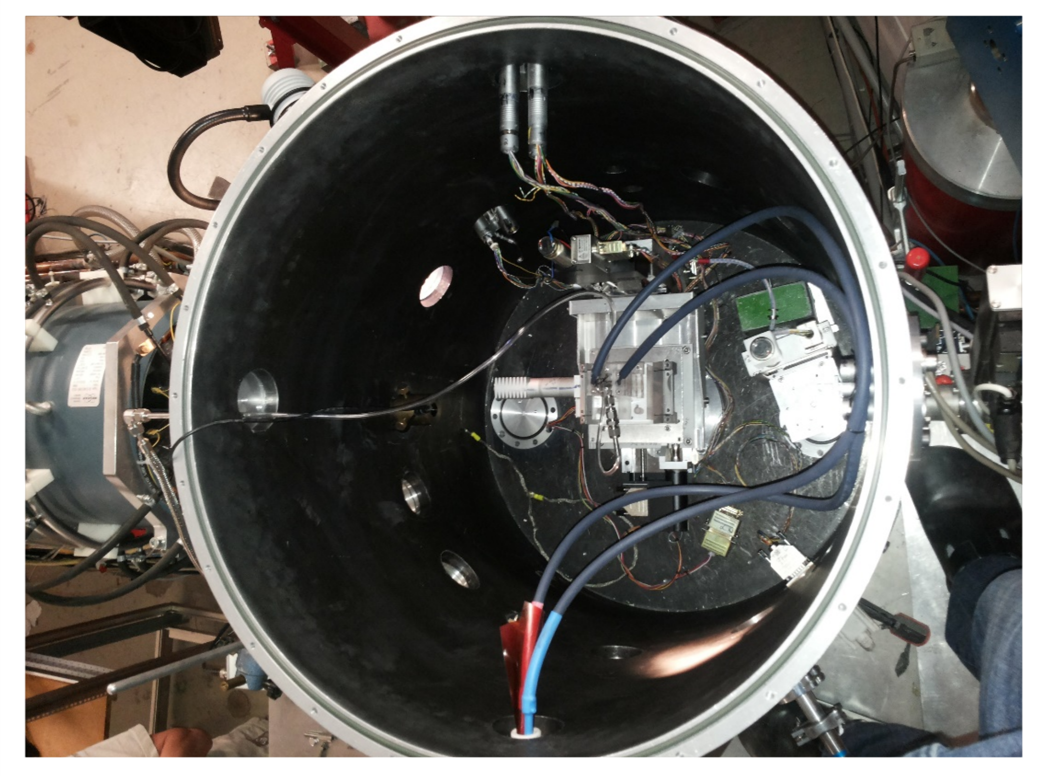
Irradiation tests with electrons at MAinzer Microtron facility (Mainz, D)

Beam intensities: 1 nA — 50 μA
Beam spot size: down to 10 μm





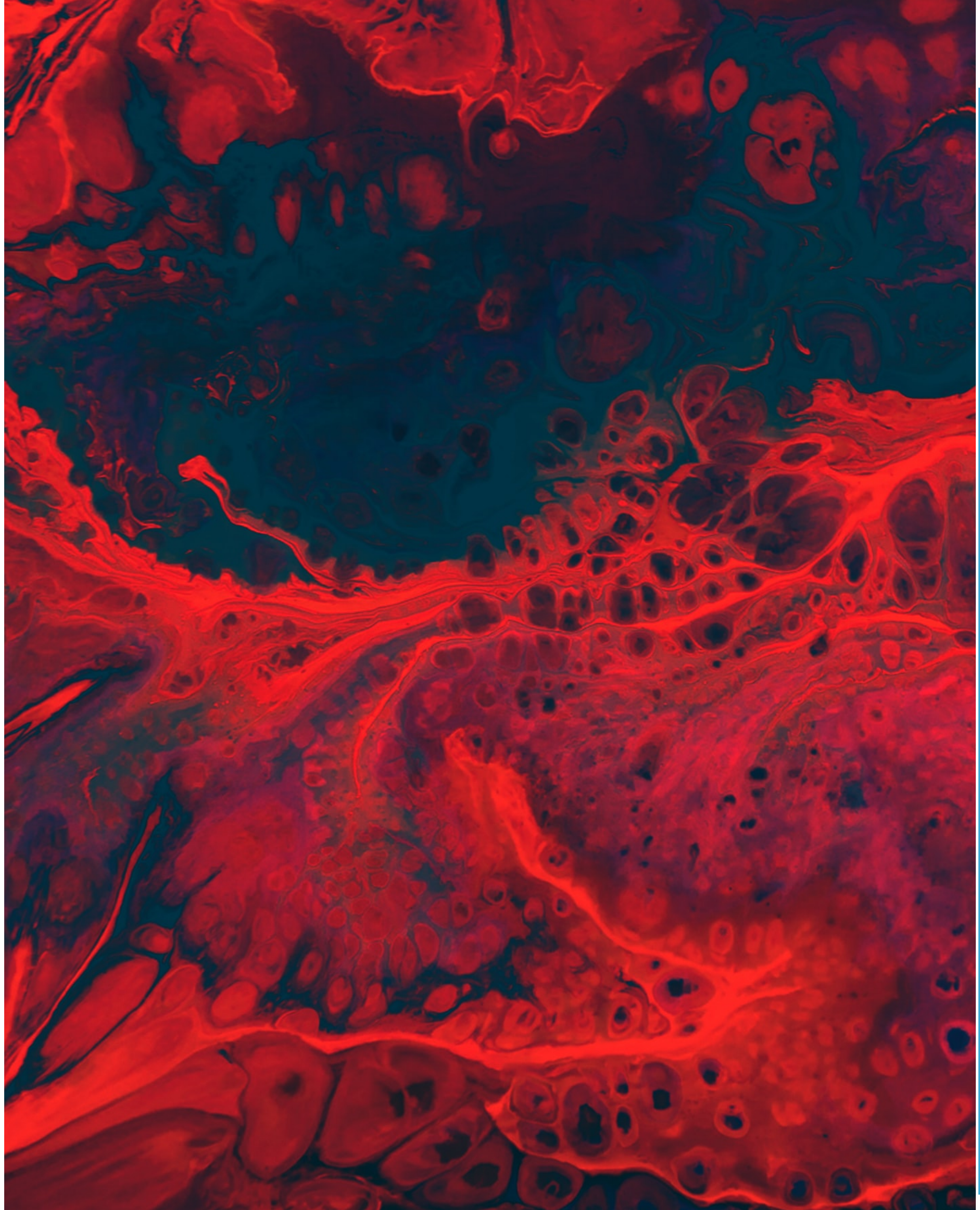
Compare model predictions with experimental data!

SUMMARY

The Muon Collider is a *dream machine* with a lot of challenges to face but the European Strategy definition gathered increasing interest in this project

- The *LEMMA option* is quite challenging and the role of target complex is crucial
- FDTD-based model to simulate target thermal evolution and thermomechanical stresses
- Planning irradiation tests for model validation and target failure studies

R&D activity ongoing for target complex optimisation!



BACKUP

"you never know what you might need"